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Created in 1849, the Department of the Interior—America's Department of Natural Resources—is concerned with the management, conservation, and development of the Nation's water, fish, wildlife, mineral, forest, and park and recreational resources. It also has major responsibilities for Indian and Territorial affairs.

As the Nation's principal conservation agency, the Department works to assure that nonrenewable resources are developed and used wisely, that park and recreational resources are conserved for the future, and that renewable resources make their full contribution to the progress, prosperity, and security of the United States—now and in the future.

ENTIFICATION OF NEW ENGLAND YELLOWTAIL FLOUNDER GROUPS

By **Fred E. Lux**, ***Fishery Biologist***, **Bureau of Commercial Fisheries**

ABSTRACT

ata from yellowtail flounder marking experiments, ray counts, and the incidence of infestation by matode parasites are reported. A distinguishable, ough not completely discrete, group of yellowtail was recognized on each of three adjoining New England grounds: a southern New England group, a Cape Cod group, and a Georges Bank group.

study of the subpopulations of the commer- lly important yellowtail flounder, *Limanda fer- inea*, was undertaken to identify clearly the loited yellowtail groups found off New gland. Data from marking experiments, ray counts, and the incidence of infestation trematode parasites were used for the purpose. sults of this study are reported here.

isheries workers have sometimes applied erent meanings to terms that are commonly d to identify fractions of fish populations. avoid misunderstanding, the terms used in s paper are therefore defined here. Definitions "population" and "group" given by Marr 57) are:

opulation.—A population of fish includes individuals of a given species when there are subspecies or, if there are subspecies when ir distributions are not discrete.

roup.—A group is a fraction of a population h distinctive characteristics, the nature of ich (phenotypic or genotypic) has not been ermined.

nder these definitions, yellowtail found off w England are members of the same pop- tion since there are no recognized subspecies. lowtail groups are the presently distinguishable ts of this population.

YELLOWTAIL FLOUNDER FISHERY

Large-scale exploitation of yellowtail began in the 1930's. Annual United States landings rose to a peak of 70 million pounds in 1942 and then declined to a low of 12 million pounds in 1954. In more recent years landings have averaged about 30 million pounds. About 70 percent of the catch is landed at New Bedford, Mass., with other southern New England ports accounting for a large part of the remainder.

Royce, et al. (1959) defined three principal yellowtail fishing grounds fished by United States vessels (fig. 1). The southern New England ground covers the area from off eastern Long Island to south of Nantucket Island (statistical subareas XXII O, Q, R, S, and area XXIII). The Georges Bank ground is the large shoal ground east of the southern New England ground (subareas XXII H, J, M, and N). The Cape Cod ground, the least important of the major grounds in terms of catch, is found off the tip of Cape Cod and extends northward along the Massachusetts coast (subareas XXII E, and G).

MARKING EXPERIMENTS

In the years 1942–49 Royce, et al. (1959) marked 2,597 fish in 14 different lots on the three principal fishing grounds. They obtained 377 recoveries. Movements were generally found to be within the grounds, but there was also some

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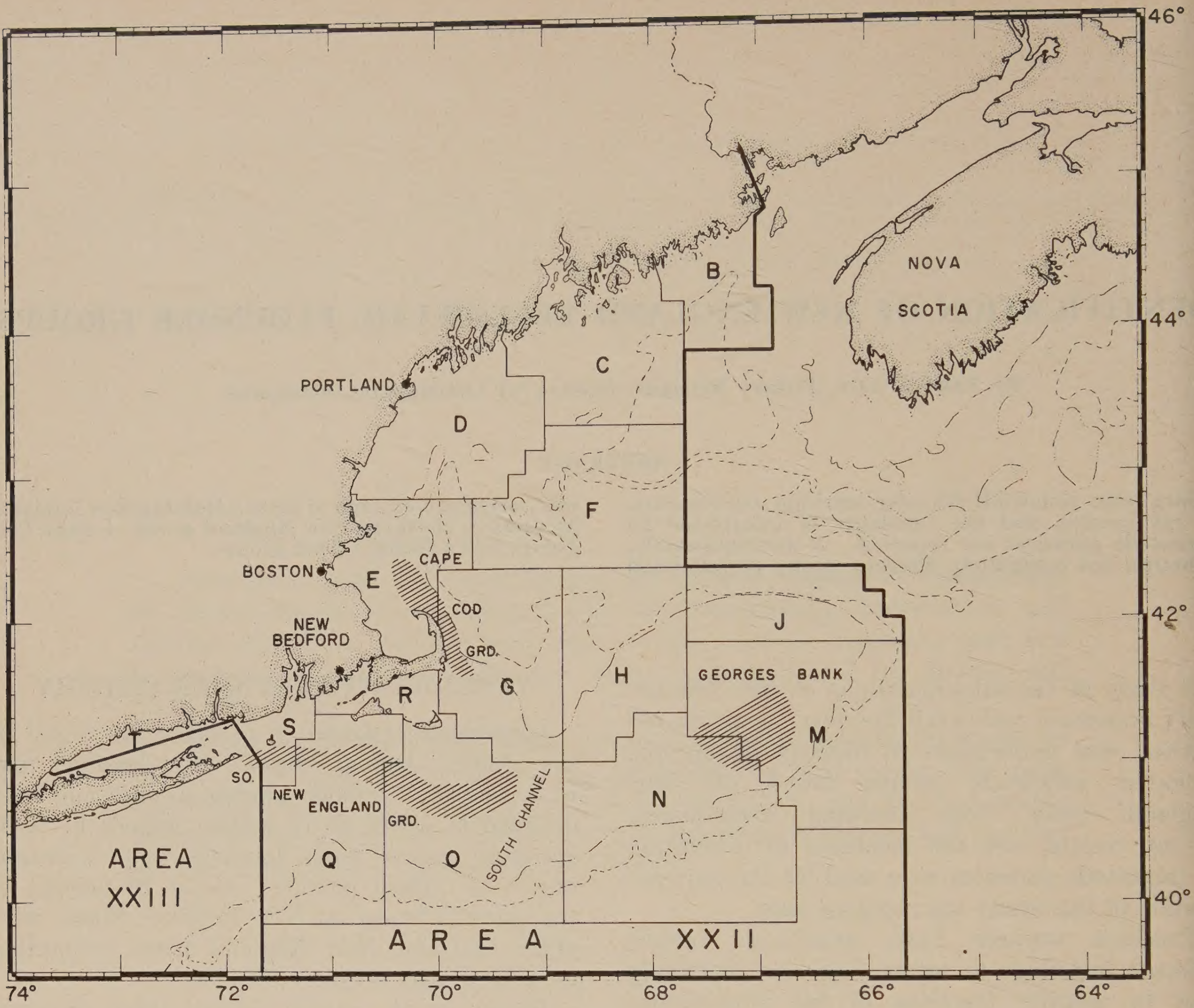

FIGURE 1.—Chart of the New England fishing areas showing the three principal grounds where yellowtail flounder are caught. Depth contours are for 50 and 100 fathoms. Statistical areas are those adopted by the North American Council on Fishery Investigations (Rounsefell, 1948).

interchange of fish between the grounds. From these results and the distribution of fishing effort, they concluded that yellowtail flounder on each of the fishing grounds were relatively separate, but that there was some intermingling between groups.

In this study 1,800 yellowtail in 12 lots were tagged and released on the three principal grounds to obtain further information on yellowtail movements and the degree of separation of fish on these grounds (table 1). There were 431 recoveries from these lots.

Recapture locations obtained from the fishermen usually were given in the form of Loran bearings for the general area of fishing operations. These locations and areas where tagged fish were released are reported in table 1 by subarea, using statistica subareas (fig. 1).

METHODS

The fish, aside from lots 7 and 8, were tagged from catches of commercial otter trawlers. Lots 7 and 8 were tagged from research vessel catches A plastic Petersen disk, $\frac{11}{16}$ inch in diameter was attached to each side of the nape of the fish with a stainless steel pin pushed through the nape One disk carried a serial number; the other, instructions to the finder. Sex of each fish and it total length in millimeters were recorded at time of tagging. Sex was determined by holding the h before a light. The ovaries extend posteriorly om the intestinal cavity along the ventral inter-emal spines and appear as a dark area. Since there is only a very slight posterior extension of the testes, no dark area is apparent in this region of males.

BLE 1.—*Areas of tagging, dates of tagging, numbers tagged, and numbers recaptured, by area and calendar quarter following tagging, for 1955 and 1957 yellowtail flounder marking experiments*

[Capital letters indicate statistical subareas]

Period of recovery	Number of fish recaptured in area												
	XXII											Unknown	Total
	E	G	H	J	M	N	O	Q	R	S	XXIII		
	Lot No. 1: 1 fish tagged April 8, 1955, XXII Q												
y-September 1956						1							1
Total						1							1
	Lot No. 2: 93 fish tagged April 21, 1955, XXII S												
il-June 1955										3		4	7
y-September 1955					1								1
ober-December 1955							1	2				1	4
uary-March 1956										2			2
il-June 1956							1						1
ober-December 1956								1		1		1	3
uary-March 1957												1	1
il-June 1957							1						1
il-June 1959												1	1
ober-December 1959								1					1
Total					1		3	4		6		8	22
	Lot No. 3: 25 fish tagged April 28, 1955, XXII Q												
il-June 1956												1	1
y-September 1956	1												1
uary-March 1957								1					1
Total	1							1				1	3
	Lot No. 4: 27 fish tagged May 9, 1955, XXII S												
y-June 1955										3			3
ober-December 1955								1					1
y-September 1956		1											1
ober-December 1956												1	1
Total		1						1		3		1	6
	Lot No. 5: 126 fish tagged June 22–24, 1955, XXII O												
e 1955							1						1
y-September 1955							1						1
ober-December 1955					2		3	4				3	12
uary-March 1956								2			2	2	6
il-June 1956							1			1		2	4
ober-December 1956							2					1	3
uary-March 1957							1	1					2
y-September 1957												1	1
ober-December 1957							2	1					3
uary-March 1958												1	1
ober-December 1958							1						1
Total					2		12	8		1	2	10	35
	Lot No. 6: 24 fish tagged July 23–26, 1955, XXII S. (No recaptures reported.)												
	Lot No.7: 7 fish tagged February 14, 1957, XXII Q												
-September 1957							1					1	2
ober-December 1957												1	1
-September 1958					1								1
il-June 1959												1	1
ary-March 1960								1					1
Total					1		1	1				3	6

TABLE 1.—*Areas of tagging, dates of tagging, numbers tagged, and numbers recaptured, by area and calendar quarter followi tagging, for 1955 and 1957 yellowtail flounder marking experiments*—Continued

[Capital letters indicate statistical subareas]

Period of recovery	Number of fish recaptured in area												
	XXII											Unknown	Tota
	E	G	H	J	M	N	O	Q	R	S	XXIII		
	Lot No. 8: 45 fish tagged February 26, 1957, XXII S												
July–September 1957					2		1	1					
October–December 1957							3	1					
January–March 1958								3					
April–June 1958							1						
July–September 1958					2								
October–December 1958							1						
January–March 1959							1						
April–June 1959							1						
January–March 1960							1						
Total					4		9	5					
	Lot No. 9: 447 fish tagged April 4 and April 12, 1957, XXII S												
April–June 1957		1						6		13			
July–September 1957							7	5				1	
October–December 1957		1					10	2					
January–March 1958								1		4	8		
April–June 1958								6	1	3		1	
July–September 1958							2						
October–December 1958					1		4	1		1			
January–March 1959								2				1	
April–June 1959								2					
July–September 1959		1											
October–December 1959							2						
April–June 1960										1			
Total		3			1		25	25	1	22	8	3	
	Lot No. 10: 547 fish tagged May 1–4, 1957, XXII G												
May–June 1957	3	79										4	
July–September 1957	11	4											
October–December 1957	4	5										3	
January–March 1958	6												
January–March 1960		1											
Total	24	89										7	1
	Lot No. 11: 28 fish tagged May 5, 1957, XXII G												
May–June 1957		6										1	
July–September 1957		1											
October–December 1957		1											
July–September 1958												1	
Total		8										2	
	Lot No. 12: 430 fish tagged August 21–23, 1957, XXII M												
August–September 1957				1	31							3	
October–December 1957				1	12							2	
January–March 1958					2			2		1			
April–June 1958					7	1							
July–September 1958				1	37	1						1	
October–December 1958			1	1	5		1						
January–March 1959					1								
April–June 1959			1										
July–September 1959					3	3						2	
Total			2	4	98	5	1	2		1		8	1

Nearly all fish marked on the southern New England and Cape Cod grounds were tagged during the spawning season in the spring. It is therefore probable that relatively pure groups were tagged on those grounds. On Georges Bank, the fish were tagged during August, considerably after the spawning season, so these fish may not hav been of a pure Georges Bank group.

A reward of one dollar was paid for each returne tag, and after May 1958 an additional dollar wa paid if the fish was returned with the tag. Mos of the recovered tags were recaptured during th

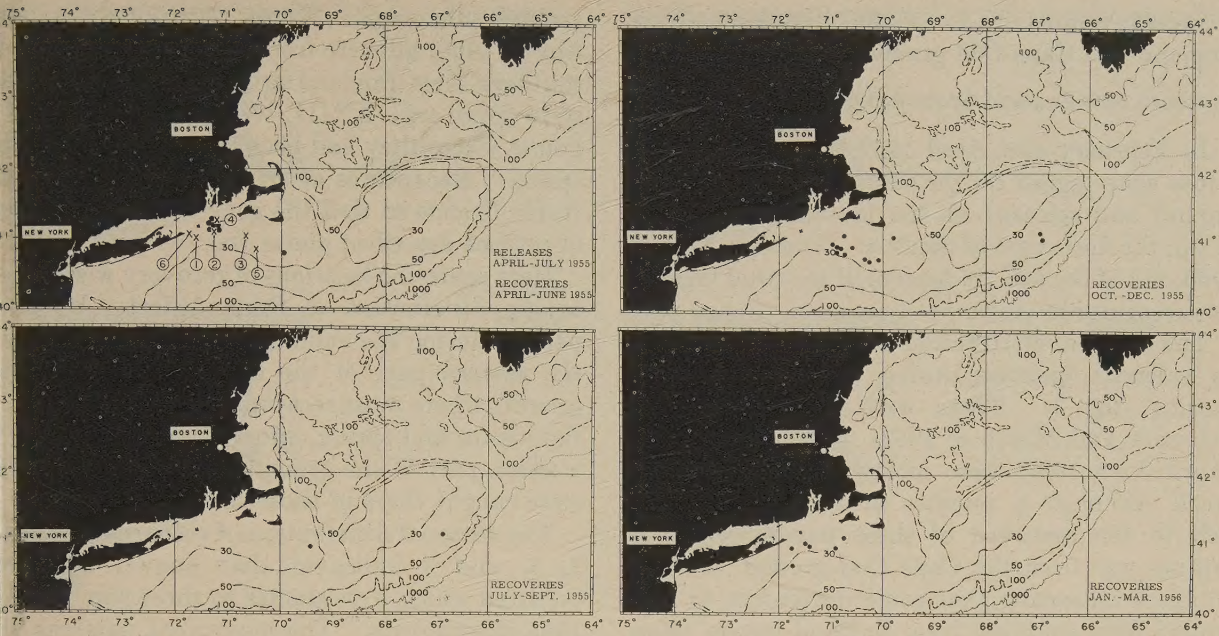

Figure 2.—Tagging on the southern New England ground, April–July 1955, lots 1 to 6. (Locations of releases indicated by X's; recoveries, by calendar quarters, indicated by dots.)

st 3 years following the release. All were taken otter trawlers.

Tags and tagged fish were recovered mostly by ermen or workers unloading catches, who gave em to Bureau of Commercial Fisheries person- stationed at ports of landing. Reliable re- very information usually accompanied these urns. Other tags were not found until the n had reached fillet plants or fish markets. covery information for these tags frequently s lacking or was unreliable.

RESULTS

uthern New England Ground, 1955

In 1955, 296 yellowtail in 6 lots were tagged d released at the locations shown by X's in the st chart of figure 2. Through August 1960, 68 the fish, 23 percent of the total tagged, were aptured (table 1).

Recaptures by calendar quarters for the first ar following tagging show the seasonal move- nt patterns (fig. 2). Spring recoveries (April– ne 1955) were mostly from areas of tagging. e two recoveries during the summer months ly–September 1955) showed that some move- nt to the eastward had occurred. One August apture had crossed Great South Channel, which arates the southern New England ground from Georges Bank, and was caught on southeastern Georges Bank, a distance of about 200 miles from release point. Fall recoveries (October–December 1955) were mostly from the middle and eastern parts of the southern New England ground, but two recaptures in October also were from subarea M of Georges Bank. Winter recoveries (January–March 1956) were caught near release points or somewhat to the westward of them.

Where tagged fish were caught depended largely upon the distribution of fishing effort. Effort was low on the southern New England ground in the summer months, and only one recapture was obtained there. In the fall, effort increased greatly, and the number of recoveries went up as well. Fishing effort on Georges Bank was highest during summer and fall months. Fish tagged on the southern New England ground were recaught on Georges Bank only in these seasons.

The pattern of recoveries for the first year after release indicated that yellowtail moved to the eastward in summer, with three tagged fish being recaught as far east as Georges Bank, and to the westward in winter months. Recaptures in subsequent years (table 1) suggest that this pattern was repeated. One fish, however, (table 1, lot 3), moved far to the northward to the Cape Cod ground, subarea E. This return was the only indication from these releases of intermingling between yellowtail from the southern New England and Cape Cod grounds.

Southern New England Ground, 1957

In February and April 1957, 499 yellowtail in 3 lots were tagged on the southern New England ground and released at the locations shown by X's in the first chart of figure 3. Through August 1960, 112 of the fish, 22 percent of the total tagged, were recaptured (table 1).

The seasonal distribution of recoveries is shown by calendar quarters during the year following tagging (fig. 3). There were no recaptures in February and March of 1957. Spring recaptures (April–June 1957) were mostly from the release areas, although a number of fish were caught well to the eastward of these points. One recapture was from the Cape Cod ground, subarea G, again indicating that some movement to this ground from southern New England waters takes place. Summer recaptures (July–September 1957) were mostly from the eastern part of the southern New England ground. However, two fish had crossed Great South channel and were caught on Georges Bank, subarea M. Fall recaptures (October–December 1957) were spread over the middle and eastern parts of the southern New England ground. In addition, one fish was recaptured on the southern part of the Cape Cod ground, subarea G. Winter recaptures (January-March 1958) all were from the western part of th southern New England ground. Several of ther were from area XXIII, well to the westward o points where they had been released the precedin spring. Recaptures after the first year at libert (table 1) showed that the general seasonal patter of returns described above was repeated.

Here again the locations of recovery were relate to the distribution of fishing effort. Effort ex pended during the summer and fall was mostly o the eastern part of the southern New Englan ground, where most recaptures were obtained. I the winter and spring, effort was primarily on th western part of the ground, and most tagged fis were caught there in those seasons.

The seasonal distribution of recoveries from lot 7, 8, and 9 indicated that annual migration occurred which were similar to those shown by th 1955 experiments. The movement patterns wer as follows: (1) There was a general movement o fish from the western to the eastern part of the south ern New England ground in spring and summer A few fish had moved as far to the eastward a Georges Bank by late summer and early fall (2) There was a general movement of fish from th eastern to the western part of the southern Ne England ground in fall and winter. (3) Ther was a small amount of movement of southern

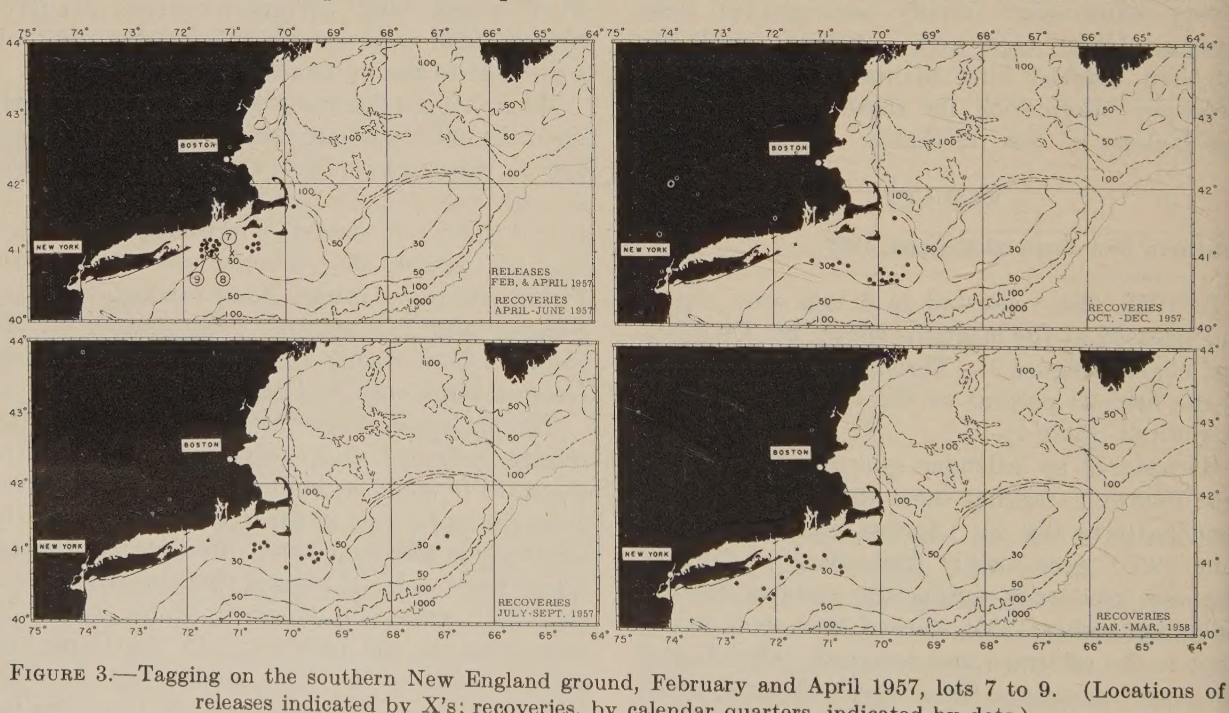
75° 74° 73° 72° 71° 70° 69° 68° 67° 66° 65° 64°
44° 43° 42° 41° 40°
BOSTON
NEW YORK
7
8
9
RELEASES FEB. & APRIL 1957
RECOVERIES APRIL-JUNE 1957
RECOVERIES OCT.-DEC. 1957
RECOVERIES JULY-SEPT. 1957
RECOVERIES JAN.-MAR. 1958
30
50
100
1000

FIGURE 3.—Tagging on the southern New England ground, February and April 1957, lots 7 to 9. (Locations of releases indicated by X's; recoveries, by calendar quarters, indicated by dots.)

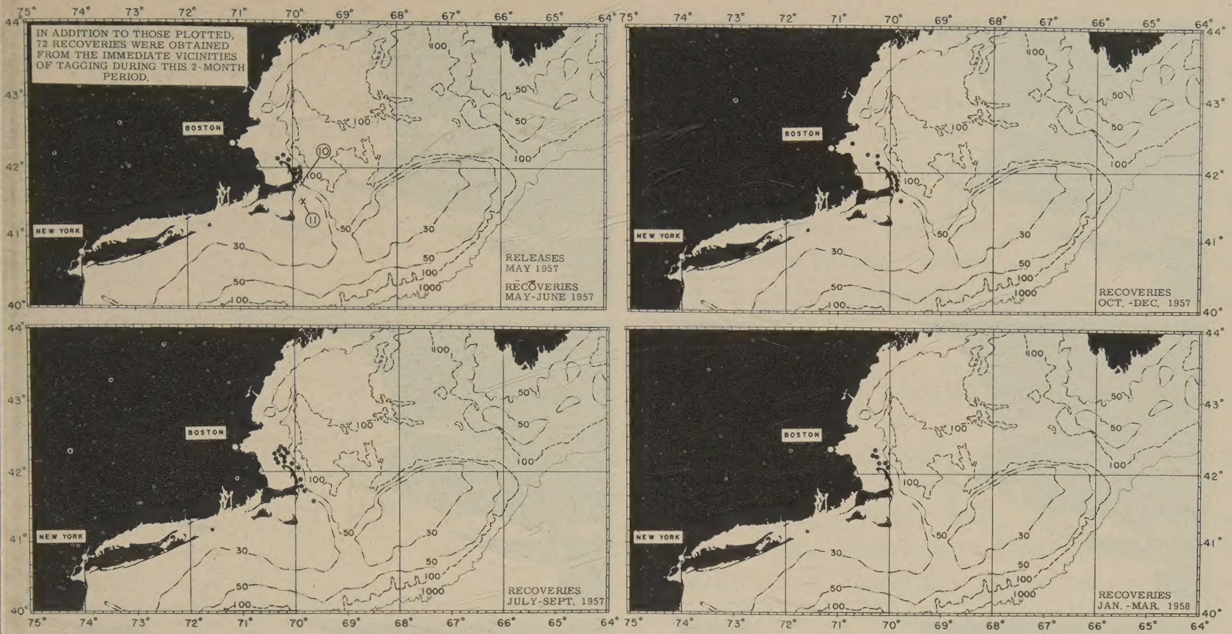
IN ADDITION TO THOSE PLOTTED, 72 RECOVERIES WERE OBTAINED FROM THE IMMEDIATE VICINITIES OF TAGGING DURING THIS 2-MONTH PERIOD.
BOSTON
NEW YORK
RELEASES MAY 1957
RECOVERIES MAY-JUNE 1957
RECOVERIES OCT.-DEC. 1957
RECOVERIES JULY-SEPT. 1957
RECOVERIES JAN.-MAR. 1958
75° 74° 73° 72° 71° 70° 69° 68° 67° 66° 65° 64°
44° 43° 42° 41° 40°
30
50
100
1000

FIGURE 4.—Tagging on the Cape Cod ground, May 1957, lots 10 and 11. (Locations of releases indicated by X's; recoveries, by calendar quarters, indicated by dots.)

ew England yellowtail to the southern part of e Cape Cod ground, but the seasonal nature of is movement was not clear.

ape Cod ground, 1957

In May 1957, 575 yellowtail in 2 lots were arked on the Cape Cod ground and released at e locations shown by X's on the first chart of gure 4. Through August 1960, 130 of the fish, percent of the total tagged, were recaptured able 1).

Recaptures by calendar quarters during the ear following tagging show the movement patrns (fig. 4). The numerous spring recaptures lay–June 1957) were mostly from the immediate cinity of tagging, although some northward ovement was indicated. Summer (July–Sepmber), fall (October–December), and winter anuary–March 1958) recaptures showed further idence of a northward movement from the lease point. Almost no recaptures were obtained om these releases after the first year following gging (table 1).

The recovery patterns on the Cape Cod ground ggest that a northward dispersal of yellowtail curred rather than an annual migration. No ovement from the Cape Cod ground to either the other two major grounds was indicated.

Georges Bank, 1957

In August 1957, 430 yellowtail were marked on Georges Bank and released at the location indicated by the X on the first chart of figure 5. Through August 1960, 121 of the fish, 28 percent of the total tagged, were recaptured (table 1).

Recapture positions for each calendar quarter in the 16 months following tagging (fig. 5) show the seasonal movements. Summer recaptures (August–September 1957) were mostly from the vicinity of marking, although one fish had moved about 40 miles to the eastward. Fall recaptures (October–December 1957) all were from Georges Bank, with two of the recoveries showing a northward movement on the Bank. Winter recaptures (January–March 1958) showed that some westward movement had occurred. Three of the five fish recaptured in this quarter had moved west across South Channel and were caught on the southern New England ground, about 200 miles west of the point of release. Spring recaptures (April–June 1958) were widely scattered about the vicinity of tagging. Summer recaptures (July–September 1958) were tightly clustered around this area. The pattern of fall recaptures (October–December 1958) was similar to that of the preceding fall, with scattered returns from over the Bank. One fall recapture, however, was from the eastern part of the southern New England

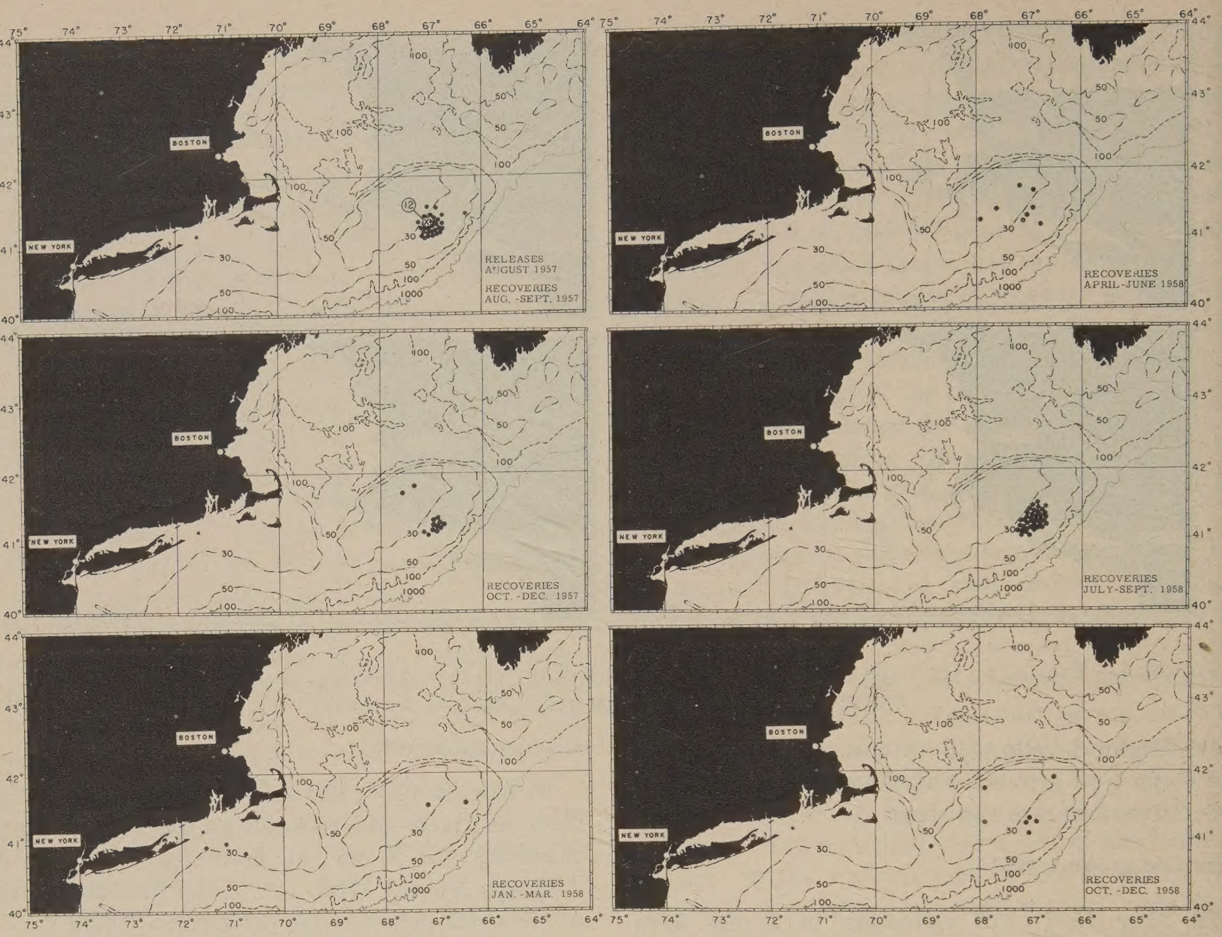
BOSTON
NEW YORK
RELEASES AUGUST 1957
RECOVERIES AUG.-SEPT. 1957
RECOVERIES APRIL-JUNE 1958
RECOVERIES OCT.-DEC. 1957
RECOVERIES JULY-SEPT. 1958
RECOVERIES JAN.-MAR. 1958
RECOVERIES OCT.-DEC. 1958
12
75° 74° 73° 72° 71° 70° 69° 68° 67° 66° 65° 64°
40° 41° 42° 43° 44°
30
50
100
1000

FIGURE 5.—Tagging on Georges Bank, August 1957, lot 12. (Location of releases indicated by the X; recoveries, by calendar quarters, indicated by dots.)

ground, subarea O, and one was from the northwestern part of Georges Bank, subarea H. Recaptures during 1959, while few in number, showed that the patterns described above were repeated (table 1).

Recovery positions of Georges Bank releases were principally determined by the distribution of fishing effort. Effort on the Bank was greatest during the summer, and it was concentrated in the vicinity where tagged fish were released. Most Georges Bank recoveries were obtained during the summer months, and they were from the area where fishing activity was greatest.

The following migration patterns were shown by yellowtail tagged on Georges Bank. (1) There was some movement to the westward during the winter months; a few of the fish were recaptured as far to the west as the southern New England ground. The fish apparently returned to the vicinity of tagging on Georges Bank in the summer. (2) Although there was some movement to other parts of Georges Bank from the release point, there was no clear migration pattern on the Bank itself. Most Bank recaptures were from area of release. (3) No movement from Georges Bank to the Cape Cod ground was indicated.

FIN RAY COUNTS

In a comparative study of Nova Scotian and southern New England yellowtail flounder, Scott (1954) investigated meristic and morphometric variation in fish from both of these areas. He found a significantly higher number of dorsal and anal fin rays in Nova Scotia yellowtail than in those from southern New England. Dorsal and anal fin ray counts were therefore selected to compare yellowtail from the New England grounds.

Frequency distributions and means of fin ray mbers for fish from the three New England ounds are given in table 2. Analysis of variance licated that there was no significant difference in ray numbers between the grounds, and it was ncluded that yellowtail from the three grounds re the same with respect to these meristic aracteristics.

BLE 2.—*Frequency distributions and mean values of ’orsal and anal fin ray numbers of yellowtail flounder rom the three principal New England grounds*

mber orsal ays	Southern New England ground 1957	Georges Bank 1957	Cape Cod ground 1957 and 1960	Number of anal rays	Southern England ground 1957	Georges Bank 1959	Cape Cod ground 1957 and 1960
------	1	--------	1	55-------	--------	--------	--------
------	--------	3	--------	56-------	1	1	4
------	2	2	1	57-------	2	4	7
------	2	2	7	58-------	5	10	7
------	8	7	8	59-------	11	22	13
------	8	12	11	60-------	7	25	20
------	10	15	11	61-------	7	15	19
------	17	19	8	62-------	5	16	11
------	15	14	17	63-------	1	8	11
------	10	15	10	64-------	1	7	5
------	7	7	10	65-------	1	4	--------
------	2	4	6	66-------	--------	1	1
------	2	4	2				
------	2	4	2				
------	--------	1	--------				
------	--------	1	--------				
------	--------	--------	1				
otals	86	110	95		41	113	98
eans	80.13	80.40	80.26		59.95	60.59	60.37

INCIDENCE OF PARASITISM

Information indicating that Cape Cod ground lowtail were geographically isolated from those the southern New England ground and Georges nk was obtained from the incidence of infesta-n by metacercariae of the trematode *Cryptocotyle gua.* A large percentage of yellowtail from nples caught on the Cape Cod ground were in-ted with this parasite. In 1958, 36 percent of fish from a sample of 370 were infested; in 59, 38 percent of the fish from a sample of 61 re parasitized. No infested fish were observed samples from either of the other grounds in se or in other years. This information sug-ts that yellowtail from the southern New gland ground and Georges Bank do not inhabit Cape Cod ground where they presumably ld become infested with the parasite.

The initial larval hosts of *C. lingua* are peri-kles, *Littorina* spp., which inhabit shoreline ters in New England (Stunkard, 1930). Cer-iae leave the periwinkles and penetrate and encyst in the skin of fishes, the cysts appearing as black, pinhead-sized specks. The metacercariae apparently remain encysted throughout the life of the host fish. The cercariae are shed only in shoal water, where periwinkles are found, and they die within about 2 days if they fail to find a host. Yellowtail on the Cape Cod ground, in order to become hosts of the parasite, must therefore be found in water close to the shore at some time during their lives.

SUMMARY AND CONCLUSIONS

Yellowtail flounder are caught on three fishing grounds off New England: the southern New England ground, the Cape Cod ground, and Georges Bank. Recoveries of fish marked on the southern New England ground showed that yellowtail there followed a migratory path that was chiefly within this ground. The fish moved to the eastward in spring and summer months and to the westward during the fall and winter. Some of the tagged fish moved greater distances, however, and were caught on the other two New England grounds. Of the 180 recoveries from southern New England tagged fish, 10 were made on Georges Bank during summer and early fall months, while 5 were made on the Cape Cod ground between late spring and early fall. This movement pattern coincided closely with the one shown by Royce et al. (1959) for the southern New England ground during the 1940’s.

Recoveries of yellowtail marked on the Cape Cod ground indicated that there was a gradual northward dispersal of fish there. None of these releases were recaught on either of the other principal grounds, indicating that they were a relatively local and stationary group. The incidence of infestation with the trematode parasite *Cryptocotyle lingua* furnished additional evidence that yellowtail of the Cape Cod group were separate from those found on the other fishing grounds. About one-third of the yellowtail from samples collected on the Cape Cod ground were infested with metacercariae of this parasite, while no infested fish were found on the other two grounds.

Recoveries of yellowtail marked on Georges Bank were mostly from area of tagging, subarea M, which is the part of the Bank that supports an intensive summer yellowtail fishery. Some of the late fall and winter recoveries were from parts of the Bank to the north and west of the tagging point, suggesting that the migratory path on Georges Bank was to the westward during winter months and to the eastward in the summer. Four of the fish moved off the Bank and were recaptured on the southern New England ground during the winter. None of the fish were recaught on the Cape Cod ground, indicating that there was no movement between the Georges Bank and Cape Cod groups.

Number of dorsal and anal fin rays were the same for all three yellowtail groups, indicating that there is no difference in these meristic characters.

Data presented here corroborate and strengthen conclusions of Royce, et al. (1959) regarding divisions of the New England yellowtail population. Each of the three principal fishing grounds supports a group of yellowtail which is essentially separate from fish on the other grounds, although a small amount of seasonal intermingling takes place between the groups.

ACKNOWLEDGMENTS

The marking experiments of 1955 were carried out by David Miller, Bureau of Commercial Fisheries Biological Laboratory, Woods Hole, Mass. His part in the tagging program is gratefully acknowledged.

Further thanks are due to the captains and crew members of the New England draggers *Portugal*, *Jacquelyn*, *Anna Grace*, *Comber*, and *Capt. Bill II*, from whose catches most of the yellowtail were tagged.

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COMPARISON OF GROWTH OF FOUR STRAINS OF OYSTERS RAISED IN TAYLORS POND, CHATHAM, MASS.

By William N. Shaw, and James A. McCann, *Fishery Biologists*

Bureau of Commercial Fisheries

ABSTRACT

Former buyers of Wareham River, Massachusetts, ed oysters claim that these oysters are slow growing nd have a high mortality rate. The purpose of this periment was to determine whether Wareham River ysters are truly slow growing.

Seed oysters from Wareham River, Mill Creek, Mas-chusetts; Long Island Sound, Connecticut; and mes River, Virginia, were suspended side by side from Fiberglas raft in Taylors Pond, Chatham, Mass. om autumn 1958 to autumn 1960. The growth rates r all strains were determined and then compared.

At the end of 1958 the Mill Creek oyster strain was gnificantly larger than the other three strains. During 1959 the growth rate of the Wareham River strain was significantly slower than those of the Long Island Sound and Mill Creek strains. During 1960 the growth rates of all strains were significantly similar. At the end of 1960 the oysters from Wareham River were significantly smaller than those from Mill Creek and Long Island Sound.

The study demonstrates that in a single environment the Wareham River oysters grow slower than oysters from Long Island Sound and Mill Creek. Further studies are necessary to determine the reasons for this apparent slow growth.

Spear and Glude (1957) demonstrated that soft ams, *Mya arenaria*, from different origins assume milar growth rates when transplanted to a new nvironment. Other investigators (Loosanoff, 949; Butler, 1952; and Andrews and McHugh, 957) had similar results with transplanting of the astern oyster, *Crassostrea virginica*. In most ases the surviving oyters adapted themselves to ne new environment and developed growth pat-erns similar to the native populations. Beaven 952), however, observed different growth rates mong four groups of oysters held in trays at olomons, Md.. He concluded that, in general, yster seed from local sources grow the best.

In autumn 1956 the Bureau of Commercial isheries Biological Laboratory at Woods Hole, ass., received a report from a commercial fish-an stating that he could no longer find buyers for Wareham River, Massachusetts, seed oysters. All former customers claimed that these oysters, which were removed from Wareham River and planted on growing grounds in areas such as Long Island Sound, Connecticut or Oyster Pond River, Chatham, Mass., grew very slowly and had a high mortality rate. They further commented that in no case did they ever recover their investment. From the above report it appeared that Wareham River oysters were possibly stunted.

Since Wareham River is capable of producing thousands of bushels of seed oysters and failures in setting are rare (Galtsoff, Prytherch, and McMillin, 1930), the Bureau of Commercial Fisheries felt that this important resource should be investigated. In 1956 studies of the history and growth of the Wareham River oyster were initiated. The purpose of this paper is to report the results of an experiment which demonstrates that

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OTE.—Approved for publication December 11, 1961.

Wareham River oysters are slow growers. Further studies will be necessary to determine the causes for the apparent slow growth.

PROCEDURE

The first phase of the investigation began with the mailing of questionnaires to all known buyers of young Wareham River oysters. Each buyer was asked when the oysters were bought, where they were planted, how many years passed before they reached market size, and what was the ratio of bushels harvested to bushels bought.

The second phase of the study dealt with a growth analysis of the Wareham River oysters which were collected from the 1958 year class. For a comparison of growth rates, seed oysters of the same year class were obtained from Long Island Sound, Connecticut; James River, Virginia; and Mill Creek, Massachusetts. The shells on which the young oysters had attached were punctured and then strung on either nylon rope, nylon parachute cord, or polyethlene tubing. The strings were then suspended side by side from a Fiberglas raft (Shaw, 1960) in Taylors Pond, West Chatham, Mass. The origin, approximate time of setting, and the date of suspension for each strain are shown in table 1.

Growth of all four groups was measured as an increase in shell height (greatest dorsoventral distance) and length (greatest anteroposterior distance). Initial measurements were taken on Oct. 30, 1958. Thereafter, except for the James River stock, each strain was measured monthly during the growing season.[1] The James River oysters were measured only four times during the study. Since 80 percent of these oysters died during the winter of 1958, the authors felt that handling of these oysters should be kept at a minimum in order to prevent further possible deaths.

Table 1.—*Origin, approximate time of setting, and date of suspension for each group of experimental oysters grown from raft in Taylors Pond, West Chatham, Mass.*

Origin	Approximate time of setting	Date of suspension
	1958	*1958*
Mill Creek, Mass	July 18–23	Sept. 2–26.
Wareham River, Mass	Aug. 1–7	Oct 7.
Long Island Sound, Conn	July 28 to Aug. 3	Oct. 15.
James River, Va	Aug. 3–21	Oct. 30.

To measure growth, approximately 100 oysters from each strain were selected. The oysters were first cleaned of all foreign matter, and care was taken not to damage any new shell deposition. They were then measured with vernier calipers to the nearest 1.0 mm. Immediately after the measurements were completed the oysters were restrung and attached to the raft.

During 1960 many of the experimental oysters, which broke away from the strings, were placed in chicken-wire bags. Since about equal numbers of oysters from each group were put in wire bags, the final growth analysis was not considered to be affected. On November 2, 1960, the last measurements were taken. The growth rates of all four groups were then determined and compared by statistical analysis.

DESCRIPTION OF AREA

The growth experiments were conducted in Taylors Pond, West Chatham, Mass. (fig. 1). The pond is about 400 yards long and 200 yards wide. Its depth ranges from 1 to 9 feet. The bottom along the shore is sand but in deeper waters changes to mud. The pond is surrounded by high cliffs which shelter the water from strong winds. From 1958 through 1960 the salinity of the pond varied from $28.22^{\circ}/_{\circ\circ}$ to $31.46^{\circ}/_{\circ\circ}$; the surface water temperatures fluctuated from a summer high of 26.7° C. to a winter low of -0.1° C.; the average pH was 7.9

ANALYSIS OF RESULTS

Answers to Questionnaire

Answers from the questionnaire were received from three companies, two on Long Island Sound, Conn., and the other at Oyster Pond River, Chatham, Mass. A total of 73,540 bushels of Wareham River oysters were bought by these firms during the years 1949–54. In all cases the oysters showed poor growth and high mortality.[3] In one instance a company planted 16,254 bushels in Long Island Sound in 1952 and 5 years later only 2,000 bushels were large enough to be sold. Since these oysters were grown in areas where native oysters do well, it appeared that the Wareham River strain was slow growing.

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[1] In Cape Cod waters the growing season generally begins in May and ends in November.

[2] The authors wish to thank Jay D. Andrews, J. Richards Nelson, and Gilbert Covell for contributing oysters used in the experiment.

[3] Possible lack of careful treatment during transportation might explain the high mortality.

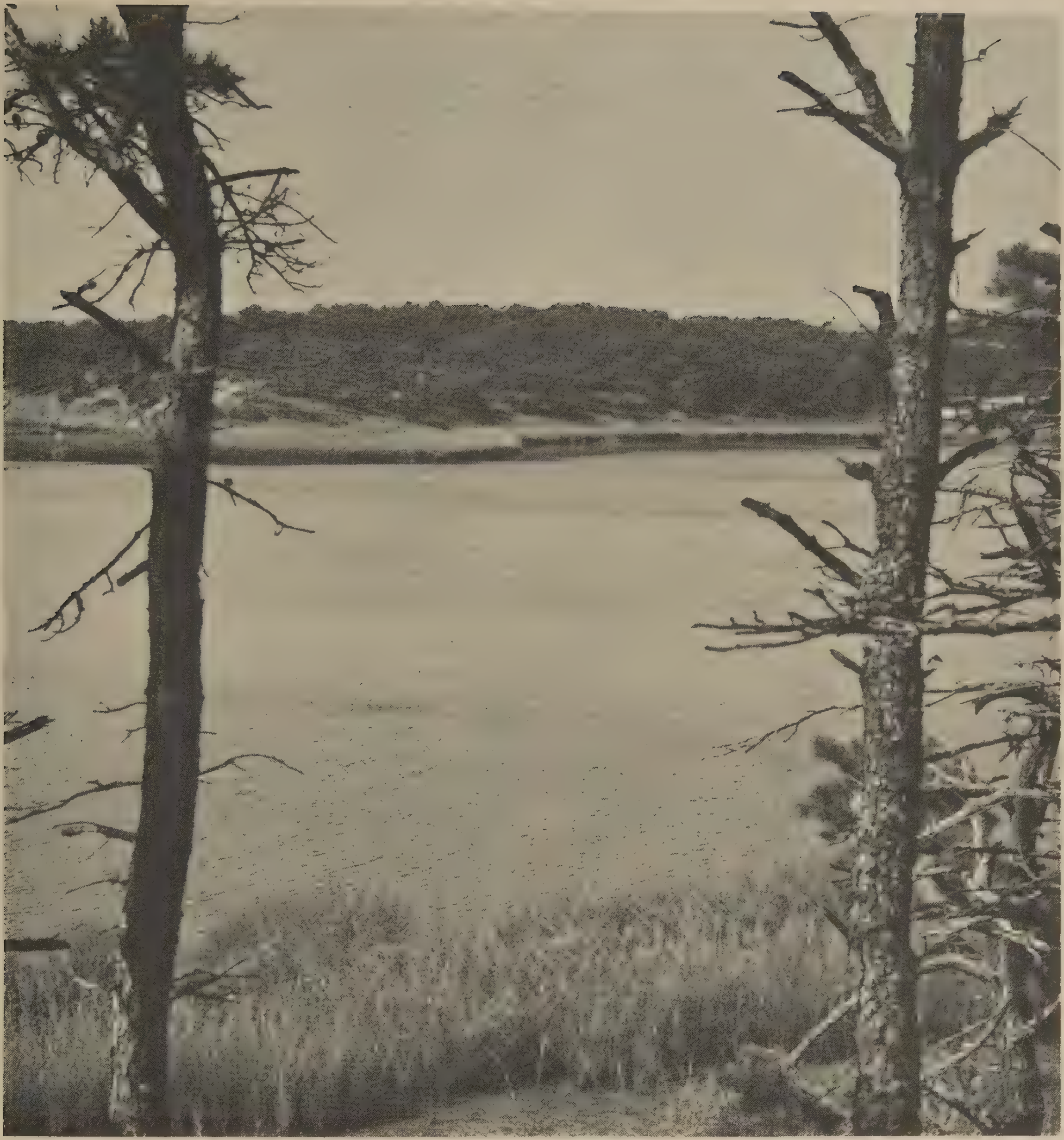

FIGURE 1.—Taylors Pond, West Chatham, Mass.

ANALYSIS OF SHELL GROWTH

As shown in table 2 and figure 2, the growth the experimental oysters varied. An analysis variance of the height data for November of 58, indicated that the differences between the an heights of the four strains were highly nificant ($F=18$). Further analysis, using a dification of the Tukey Method (Snedecor, 56), showed that a difference between the means al to or larger than 1.99 ($Q_{.05}S_{\bar{n}}$) was significantly different. Thus the mean height of the Mill Creek oysters was significantly greater than the heights of the other three strains by the end of 1958.

These differences in mean heights at the end of 1958 were more than likely due to the fact that the initial time of setting was not the same for all four groups. Setting in Mill Creek occurred between July 18 and 23, while setting in the other three areas did not take place until 5–29 days later

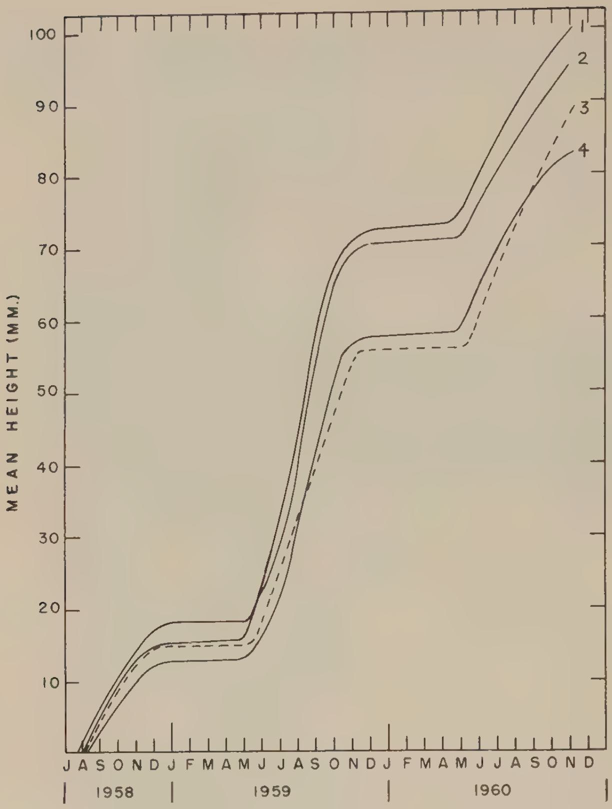

FIGURE 2.—Growth curves for strains of oysters attached to raft in Taylors Pond. Origin of oysters was as follows: 1. Long Island Sound; 2. Mill Creek; 3. James River; and 4. Wareham River.

TABLE 2.—*Total yearly mean growth of experimental oysters in Taylors Pond for the years 1958, 1959, and 1960. Based on the difference between total height and initial height for each growing season*

Origin	1958	1959	1960
	mm.	*mm.*	*mm.*
Long Island Sound	15.4	57.3	26.8
Mill Creek	18.4	52.1	24.6
Wareham River	13.0	45.3	24.6
James River	13.9	42.4	32.1

(table 1). It is, therefore, logical that oysters with the earliest start, in this case the Mill Creek stock, were the largest at the end of the setting year,[4] while the oysters with the latest start, in this case the Wareham River and James River stocks, were the smallest.

In 1959 the Long Island Sound oysters grew 57.3 millimeters and the Mill Creek oysters grew 52.1 mm. At the same time, the Wareham River and James River oysters grew only 45.3 mm. and 42.4 mm., respectively (table 2). From these data it appears that the Long Island Sound and Mill Creek strains grew faster than the other two groups. When the growth curves for 1959 are examined (fig. 2), the differences in growth are apparent.

An analysis of variance of the height data at the end of the 1959 growing season indicated that the differences between the means were again highly significant. Further analysis ($Q_{.05}S_{\bar{n}}=6.50$) showed that the means of the Long Island Sound and Mill Creek strains were significantly greater than the Wareham River and James River strains, but the Long Island and Wareham River strains were not significantly different from the Mill Creek and James River strains respectively.

Assuming the growth rate of each strain was linear within a single growing season, a comparison of the growth rates of the three strains[5] was made by using covariance analysis. This comparison during the 1959 growing season indicated that the growth rates were significantly different at the 5-percent level. Further analysis using the t-test (Snedecor, 1956) showed that the growth rates of the Mill Creek and Long Island Sound strains were significantly faster than the growth rate of the Wareham River strain (fig. 3).

An analysis of variance of the data at the end of 1960 indicated that the differences between the means were significantly different. Closer examination showed the relationship of the four strains ($Q_{.05}S_{\bar{n}}=5.88$) had not changed from the previous year. An analysis of convariance also indicated the growth rate for the four strains were also statistically similar (fig. 4). It is also interesting to note that on comparing the regression coefficients for both years, the growth rates for all strains in 1960 was about one-half as fast as that in 1959.

COMPARISON OF WEIGHTS AND VOLUMES

The question arose whether the selection of shell height as measurement for comparing growth differences between oyster strains gave reliable results. To check our findings, a random sample of 25 oysters was selected from each experimental strain on November 2, 1960. The total weight, weight of shell, weight of meat and liquor, wet weight of meat, and total volume of meat and liquor were determined for each sample and then compared (table 3).

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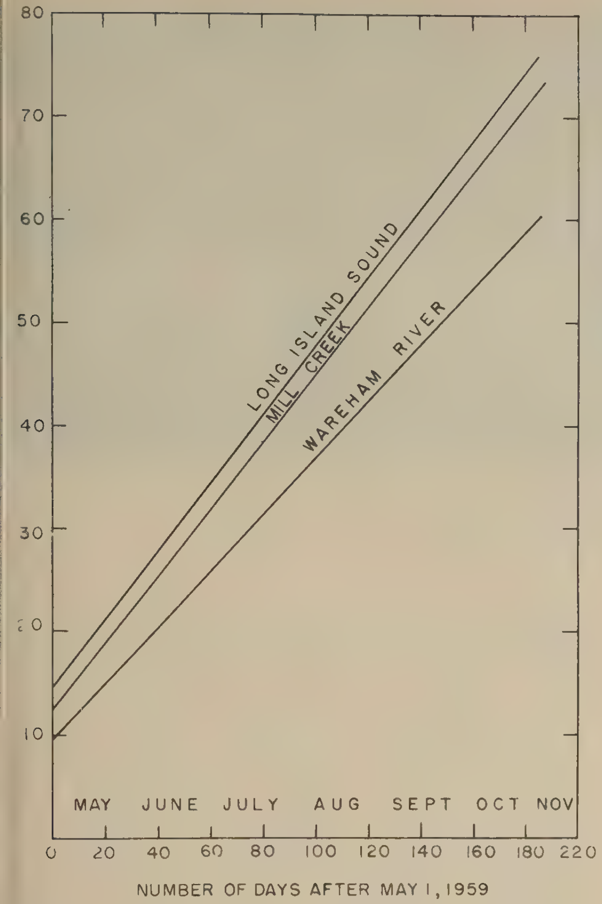
[4] From time of setting to January 1 is the setting year.

[5] Not enough data to include James River strain for 1959.



IGURE 3.—Growth rate regressions of three strains of oysters cultured in Taylors Pond, Chatham, Mass., during the 1959 growing season.

ABLE 3.—*Total weight, weight of shell, weight of meat and liquor, and weight of meat for 25 oysters selected from each strain on Nov. 2, 1960*

[Measurements in grams]

Origin	Total weight	Weight of shell	Weight of meat and liquor	Weight of meat
ng Island Sound	2,560	1,920	637.7	370.9
ill Creek	2,210	1,660	555.5	333.6
mes River	2,010	1,560	448.1	260.8
areham River	1,830	1,370	464.4	281.3

The data clearly showed that the oysters from ong Island Sound and Mill Creek have greater eights in all categories than the corresponding eights for oysters originating in the James River d the Wareham River (table 3). Likewise, the rmer two strains have greater meat and liquor lumes than the latter (figure 5). The above eight and volume comparisons between strains e similar to the results obtained when the mean heights for these strains were compared at the end of 1960 (fig. 2). It seems, therefore ,that the use of shell height is justified in this experiment.

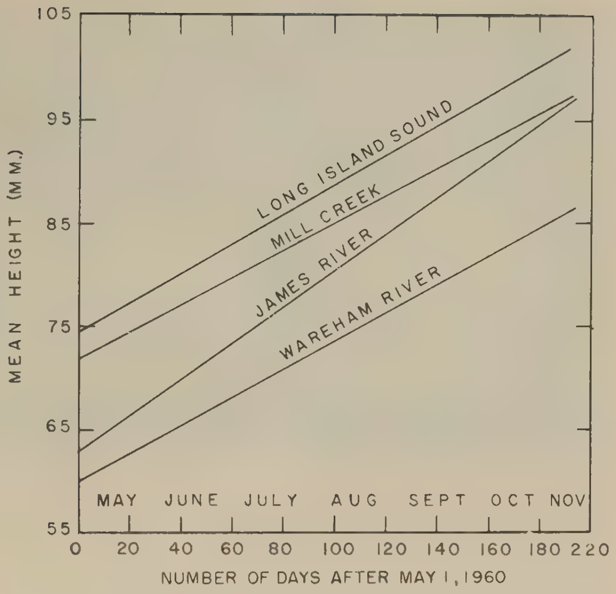


FIGURE 4.—Growth rate regressions of four strains of oysters cultured in Taylors Pond, Chatham, Mass., during the 1960 growing season.

MORTALITY

As mentioned earlier, the James River oysters had a mortality of 80 percent during the winter of 1958. Little further mortality of these oysters was observed either in 1959 or 1960. Mortality among the other strains was less than 10 percent from the fall of 1958 until the spring of 1960. During 1960 approximately 32.5, 22.4, and 6.3 percent of the Mill Creek, Wareham River, and Long Island Sound oysters died, respectively.

The high mortality among the Mill Creek and Wareham River strains in 1960 was attributed to the fact that many of these oysters, which had originally set on bay scallop shells, broke away from the strings and fell to the bottom. The scallop shells apparently were unable to support the additional weight of the growing oysters and, consequently, fell apart. The low mortality among the Long Island Sound oysters in 1960 can probably be attributed to these oysters being originally caught on oyster shells which were able to support the additional weight.

FUTURE RESEARCH

Our study shows clearly that the Wareham River oysters grow slower than oysters originating

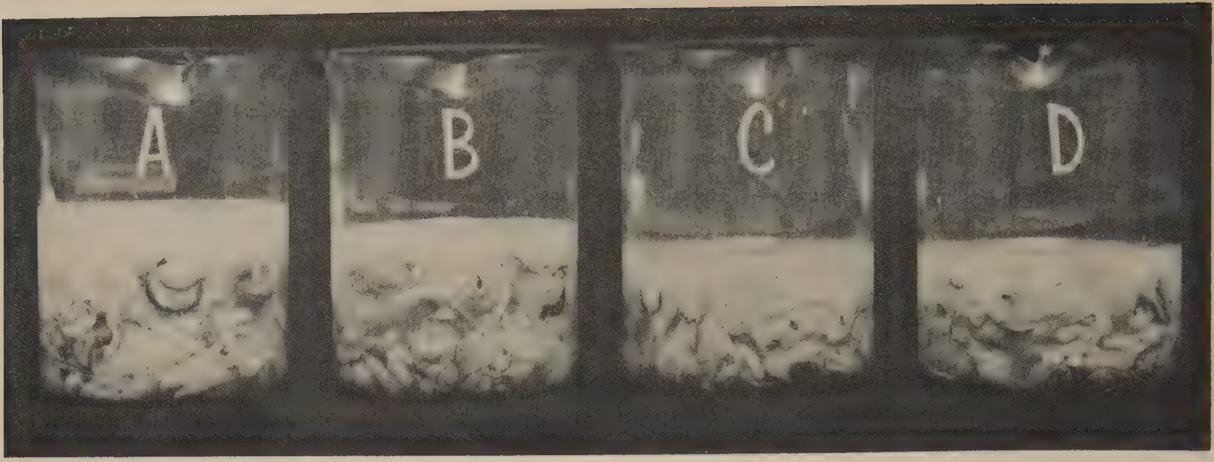


Figure 5.—Total meat and liquor volumes for 25 oysters selected from each strain on Nov. 2, 1960. Origin of oysters was as follows: A. Long Island Sound; B. Mill Creek; C. Wareham River; and D. James River.

from Long Island Sound and Mill Creek. The evidence suggests that the slow growth may be caused by hereditary characteristics. One should not overlook the possibility that the growth of this strain might be the results of environmental conditions which occurred during either embryonic or larval stages. The true answer must await further laboratory and field experiment.

SUMMARY

1. Former buyers of Wareham River seed oysters claim that these oysters are slow-growing and have a high mortality rate.

2. The purpose of the experiment was to determine whether the Wareham River oysters are slow-growing. The determination was made by comparing the rate of growth of this strain with the rates of growth of oysters from other areas.

3. Seed oysters from Wareham River, Mill Creek, Long Island Sound, and James River were suspended side by side from a raft in Taylors Pond, Chatham, Mass.

4. Growth for each strain was measured by monthly samples taken during the growing season.

5. At the end of 1958, the mean heights of the Long Island Sound, Wareham River, and James River strains were significantly smaller than the mean height of the Mill Creek strain.

6. During 1959, the growth rate of the Wareham River strain was significantly slower than the growth rates of the Long Island Sound and Mi Creek strains. The average height of the Wareham River strain at the end of 1959 was significantly smaller than the average heights of the Long Island Sound amd Mill Creek strains.

7. During 1960, the growth rates of all strains were significantly similar. The average height of the Wareham River strain at end of 1960 was still significantly smaller than the average heights of the Long Island Sound and Mill Creek strains.

8. A comparison of total weight, weight of shell, weight of meat and liquor, wet weight of meat, and total volume of meat and liquor showed that the oysters from Long Island Sound and Mill Creek had greater weights and volumes in all categories than the corresponding weights and volumes for oysters from Wareham River and James River.

9. Mortality among the Wareham River, Long Island Sound, and Mill Creek strains was less than 10 percent from autumn 1958 until spring 1960. Approximately 32.5, 22.4, and 6.3 percent of the Mill Creek, Wareham River, and Long Island Sound strains died, respectively, during the remainder of 1960. About 80 percent of the James River oysters died during the winter of 1958.

10. The results of the experiment indicates that the Wareham River oysters grow slower than oysters originating from Long Island Sound and Mill Creek. Further research is necessary to determine the causes for the apparent slow growth.

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HERRING TAGGING EXPERIMENTS IN SOUTHEASTERN ALASKA

By BERNARD EINAR SKUD, *Fishery Biologist*
BUREAU of COMMERCIAL FISHERIES

ABSTRACT

Results of herring tagging experiments in south- stern Alaska during 1934–37 were studied to provide ckground information for more recent taggings. ecovered tags evidenced extensive movement and termingling between Sitka and Craig stocks, which ere previously considered discrete. Tagging was ncentrated on a single year class during these 4 years, d the extent of the migrations apparently increased th age of the herring.

Total mortality increased with each year of recovery in each experiment, and successively later experiments indicated higher mortality rates. The fishing effort exhibited a general decline during this period. These results coupled with the concentration of tagging on a single year class support the conclusion that natural mortality increases with age.

Recommendations for future tagging in southeastern Alaska are included in the discussion.

Results of tagging experiments and racial studies herring (*Clupea harengus pallasi*) in southeast- n Alaska have influenced existing management ractices in the commercial fishery. Rounsefell d Dahlgren (1933) and Dahlgren (1936), report- on tagging experiments conducted to 1935, but sults of subsequent tagging in 1936 and 1937 ve not been published. In recent years the ed for additional tagging studies has been phasized by three factors:

1. The recent changes in fishing areas.
2. The contention of salmon trollers that local rring populations have been seriously depleted the commercial reduction fishery.
3. The exclusion of herring in the North Pacific reaty rights of abstention.

Detailed information on mortality, migratory tterns, and degree of intermingling among races herring is needed to answer questions which ise from these problems. Before undertaking ditional tagging studies, it is both logical and pedient to gather as much background informa- n as possible. The purposes of this paper are to provide a summary and analysis of results from previous experiments that may serve as a guide and basis for subsequent tagging.

TAGGING AND RECOVERIES

As pointed out by Rounsefell and Dahlgren (1933), conventional external tagging and marking experiments on herring before 1930 had not been successful. To test the feasibility of tagging herring, they began a study at Holmes Harbor in Puget Sound, Washington, during 1932. The study was designed to provide information on the following points:

1. The relative merits of different tagging methods.
2. The mortality of tagged or marked herring.
3. The development of a field technique for tagging.
4. A method of recovery suitable for a reduction fishery.

The results of this study and the initial experiments in southeastern Alaska showed that tagging on an extensive scale was practical. Rounsefell and Dahlgren (1933) and Dahlgren (1936) pre-

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sented detailed information on the methods and procedures used in tagging and recovery. Internal metal tags were found to be superior to external tags, both from the standpoint of low mortality caused by tagging and adaptability of the technique to field conditions. An electromagnet was designed to provide a mechanical means of recovering metal tags from fish meal, and later an electronic detector was developed to recover tags before the fish were processed. Detectors were not installed in all of the reduction plants, and the majority of recoveries were from electromagnets. Dahlgren (1936) emphasized the limitations of the magnet recoveries.

The allocation of tags to specific areas of catch was, at times, impractical or uncertain, and such recoveries were designated "area unknown" or "doubtful." On the other hand, when fishing was concentrated within a restricted area for an extended period, recoveries could be reliably assigned to a specific area. Further, the recapture area of tags recovered by the magnet was in many cases substantiated by tags recovered from the electronic detector. Also, though isolated recoveries were classified as "doubtful," multiple recoveries from a given area reduced the error of assigning such an area as a possible point of recovery.

From 1930 to 1940, the southeastern Alaska herring reduction fishery was concentrated on two stocks. The spawning beaches of these stocks centered about Sitka on the west coast of Baranof Island, and in the vicinity of Craig on the west coast of Prince of Wales Island. Other stocks in southeastern Alaska contributed relatively minor catches to the reduction fishery, and tagging was concentrated in the Sitka and Craig areas.

In each year, fish were tagged in the spring, and recoveries were made during the summer fishing period, June through September. For management purposes, the fishery had been divided into two general areas which were utilized for a breakdown of tag recoveries:

1. The Cape area encompassing the entire west and southeast coasts of Baranof Island. Sitka is located in this area (fig. 1).

2. The non-Cape area, including the west coasts of Kuiu and Prince of Wales Islands and the lesser islands in the vicinity. Craig is located in this area (fig. 1).

In summarizing the results of published tagging experiments, a listing of the original data is not warranted in this report, and only a gross examination of these data and unpublished data from tagging studies in 1936 and 1937 will be considered.

Table 1.—*Recoveries from Sitka tagging experiments*

Year of tagging	Number tagged	Year of recovery	Number and locality of recovered tags								Total
			Non-Cape area			Non-Cape or Cape		Cape area		Unknown	
			Warren Island	Kuiu Island	Other	Warren or Ommaney	Kuiu or Ommaney	Cape Ommaney	Other		
1934	11,964	1934	14	7	0	5	0	463	1	6	496
		1935	11	0	0	14	0	71	2	110	208
		1936	4	3	3	3	0	10	5	10	38
		1937	0	7	0	0	0	3	4	0	14
		1938	0	1	0	1	0	1	1	0	4
Total			29	18	3	23	0	548	13	126	760
1935	27,911	1935	86	0	0	113	0	929	68	878	2,074
		1936	87	35	21	20	120	233	34	97	647
		1937	0	130	0	4	111	97	22	21	385
		1938	0	7	0	1	5	26	2	2	43
		1939	0	0	0	0	0	1	0	1	2
Total			173	172	21	138	236	1,286	126	999	3,151
1936	10,784	1936	26	16	7	6	80	184	29	53	401
		1937	1	58	1	3	69	70	8	7	217
		1938	0	2	0	0	3	11	1	0	17
		1939	0	0	0	0	0	0	0	1	1
Total			27	76	8	9	152	265	38	61	636
1937	14,021	1937	0	50	1	3	94	122	20	12	302
		1938	0	3	0	0	1	22	2	5	33
		1939	0	0	0	0	0	1	0	0	1
Total			0	53	1	3	95	145	22	17	336
Grand total			229	319	33	173	483	2,244	199	1,203	4,883

rom 1934 through 1937, 100,911 tags were in-
rted in herring from the Cape and non-Cape
eas. The number of insertions at Sitka totaled
,680 from which there were 4,883 recoveries
able 1). At Craig the number of insertions was 36,231, from which there were 1,114 recoveries (table 2).

Most recoveries from the Sitka experiments were taken in the Cape area, whereas most recoveries from the Craig experiments were taken

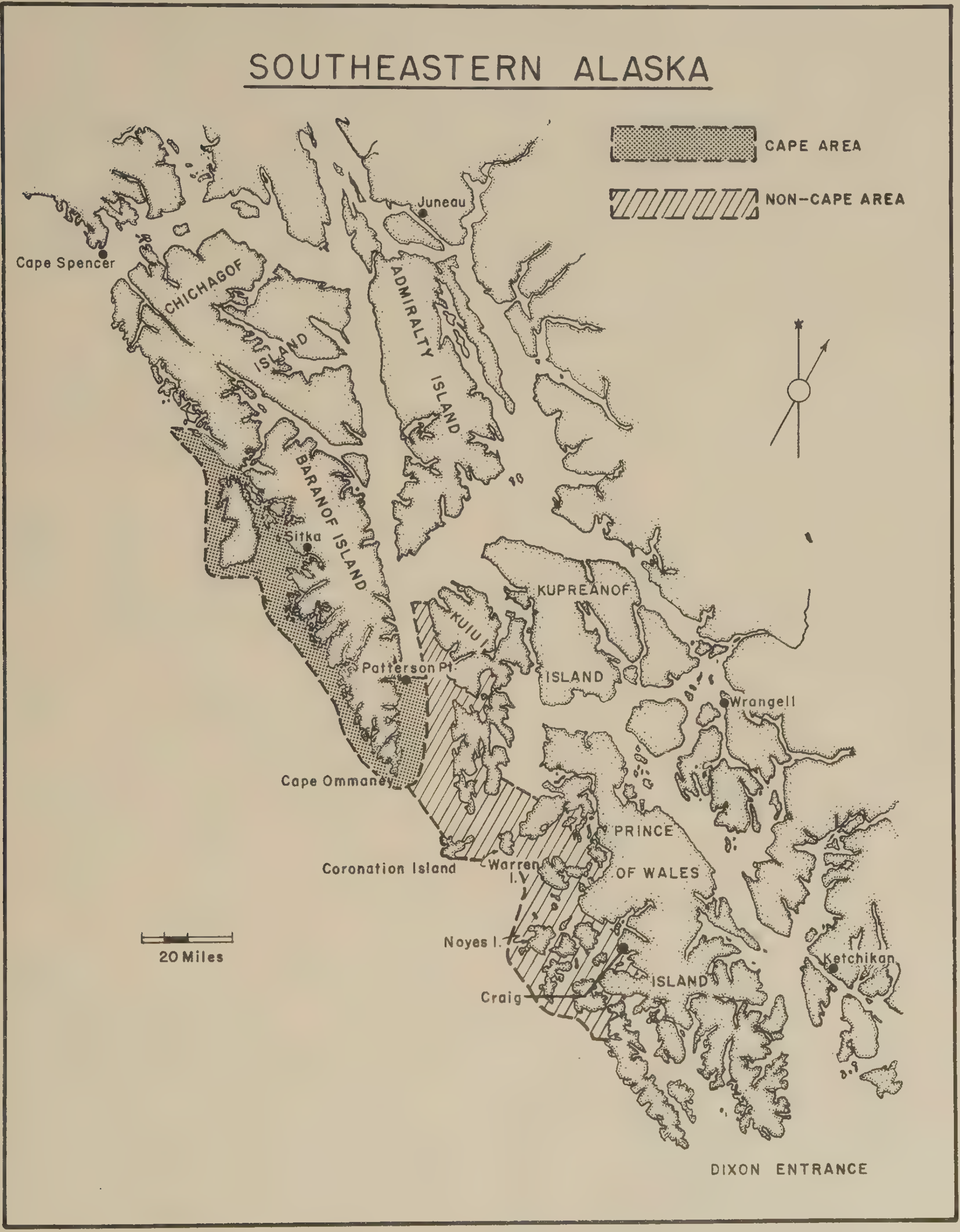

SOUTHEASTERN ALASKA
CAPE AREA
NON-CAPE AREA
Juneau
Cape Spencer
CHICHAGOF ISLAND
ADMIRALTY ISLAND
BARANOF ISLAND
Sitka
KUPREANOF ISLAND
KUIU I.
Patterson Pt.
Wrangell
Cape Ommaney
PRINCE OF WALES ISLAND
Coronation Island
Warren I.
Noyes I.
Craig
Ketchikan
20 Miles
DIXON ENTRANCE

Figure 1.—Southeastern Alaska showing Cape and non-Cape areas of the herring fisheries.

TABLE 2.—*Recoveries from Craig tagging experiments*

Year of tagging	Number tagged	Year of recovery	Number and locality of recovered tags								Total
			Non-Cape area			Non-Cape or Cape		Cape area		Unknown	
			Warren Island	Kuiu Island	Other	Kuiu or Ommaney	Cape Ommaney	Ommaney	Other		
1934	7,439	1934	78	1	0	5	3	62	0	0	149
		1935	24	0	0	13	0	18	1	27	83
		1936	10	3	2	2	4	5	1	3	30
		1937	0	9	0	1	4	1	1	1	17
		1938	0	1	0	0	0	2	0	0	3
Total			112	14	2	21	11	88	3	31	282
1935	13,008	1935	74	0	0	61	0	31	0	117	283
		1936	34	14	26	10	13	25	4	49	175
		1937	0	42	1	3	28	12	5	6	97
		1938	0	0	0	0	2	4	1	1	8
Total			108	56	27	74	43	72	10	173	563
1936	4,880	1936	20	3	15	0	10	7	0	18	73
		1937	0	34	2	0	20	8	1	3	68
		1938	0	6	0	0	2	1	0	0	9
Total			20	43	17	0	32	16	1	21	150
1937	10,904	1937	0	49	6	1	27	7	4	4	98
		1938	0	0	7	0	5	6	0	0	18
		1939	0	0	0	0	0	0	0	3	3
Total			0	49	13	1	32	13	4	7	119
Grand total			240	162	59	96	118	189	18	232	1,114

in the non-Cape area. Although recoveries were initially designated by exact location of the catch, the low number of recoveries in certain localities discourages analyses that are based on such specific assignment. Rather, possible discrepancies are considered minimized by designating recoveries to more general areas. Unknown and uncertain recoveries have been assigned to the two areas in the same proportion as known recoveries.

MIGRATIONS

Though the distribution of recoveries in the Cape and non-Cape areas from each experiment follows a general pattern of fluctuation, the annual variations in locality distribution of recovered tags shown in tables 1 and 2 merit attention. Variations of fishing effort expended in the areas will, of course, influence the number of tag recoveries and must be considered in the analyses. The practice in the herring fishery has been to measure effort in ton-days. This unit represents the net tonnage of vessels utilized and the number of vessel-days fished and provides an index comparable with the early years of the fishery when vessels were smaller than in recent years. Large vessels were found to be more efficient than small ones. Rounsefell (1930) discussed the significance of change in vessel size to 1929 and the accompanying graph (fig. 2) extends Rounsefell's data to the 1955 fishery. The average vessel size during the period of tagging experiments (1934–39) was relatively stable.

The effort expended in the Cape and non-Cape areas was obtained from records maintained by vessel and plant operators. The ratio of recoveries to effort in each recovery year from successive tagging experiments at Sitka and Craig are compared in tables 3 and 4 and figures 3 and 4.

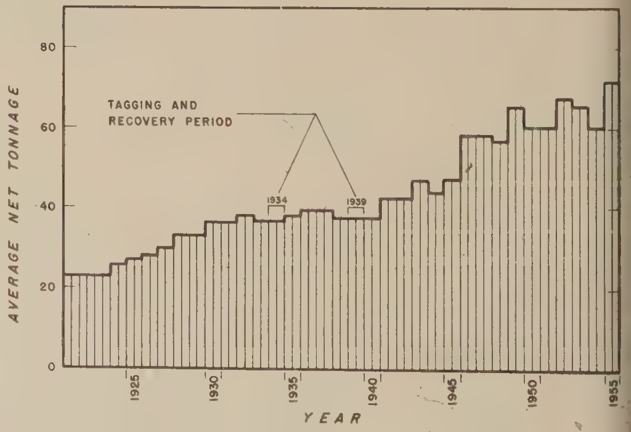
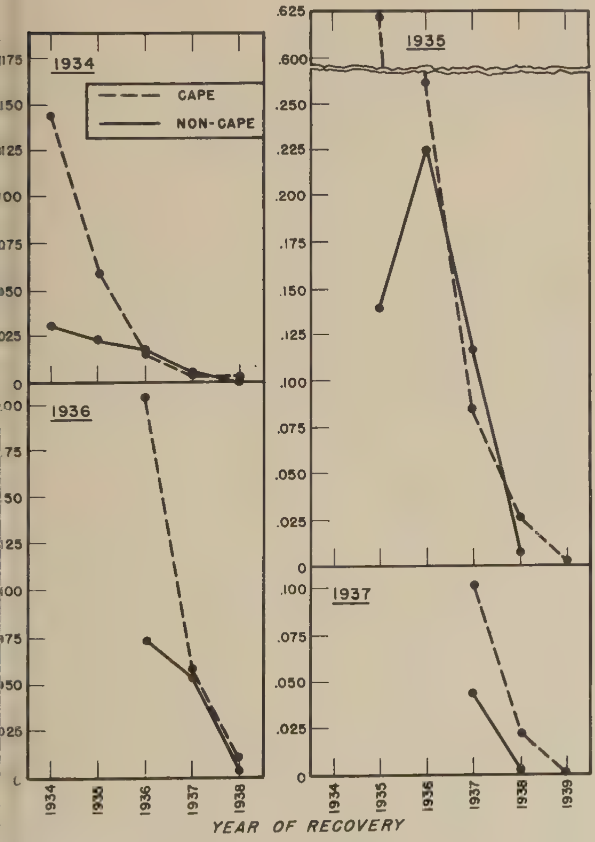


FIGURE 2.—Average net tonnage of herring vessels in southeastern Alaska, 1921–55.

BLE 3.—*Fishing effort and recoveries of Sitka tagging experiments*

Year of tagging	Year of recovery	Cape area			Non-Cape area		
		Effort in ton-days *f*	Recoveries *R*	$\frac{R}{f}$	Effort in ton-days *f*	Recoveries *R*	$\frac{R}{f}$
4	1934	3, 278	474	0. 1446	693	22	0. 0317
	1935	3, 065	181	. 0591	1, 200	27	. 0225
	1936	1, 604	23	. 0143	1, 005	15	. 0149
	1937	2, 147	7	. 0033	1, 743	7	. 0040
	1938	1, 294	3	. 0023	1, 136	1	. 0009
5	1935	3, 065	1, 909	. 6228	1, 200	165	. 1375
	1936	1, 604	421	. 2625	1, 005	226	. 2249
	1937	2, 147	184	. 0857	1, 743	201	. 1153
	1938	1, 294	34	. 0268	1, 136	9	. 0079
	1939	898	2	. 0022	1, 806	0	0
6	1936	1, 604	326	. 2032	1, 005	75	. 0746
	1937	2, 147	123	. 0573	1, 743	94	. 0539
	1938	1, 294	14	. 0108	1, 136	3	. 0026
	1939	898	0	--------	1, 806	0	0
7	1937	2, 147	215	. 1001	1, 743	77	. 0442
	1938	1, 294	29	. 0224	1, 136	4	. 0035
	1939	898	1	. 0011	1, 806	0	0

he results show that the vulnerability of tagged h from each Sitka experiment is greater in the ape area than the non-Cape area during the st years of recovery; but that vulnerability in bsequent years is about equal in the two areas.



GURE 3.—Sitka tagging experiments: the ratio of tag recoveries to effort in the Cape and non-Cape areas.

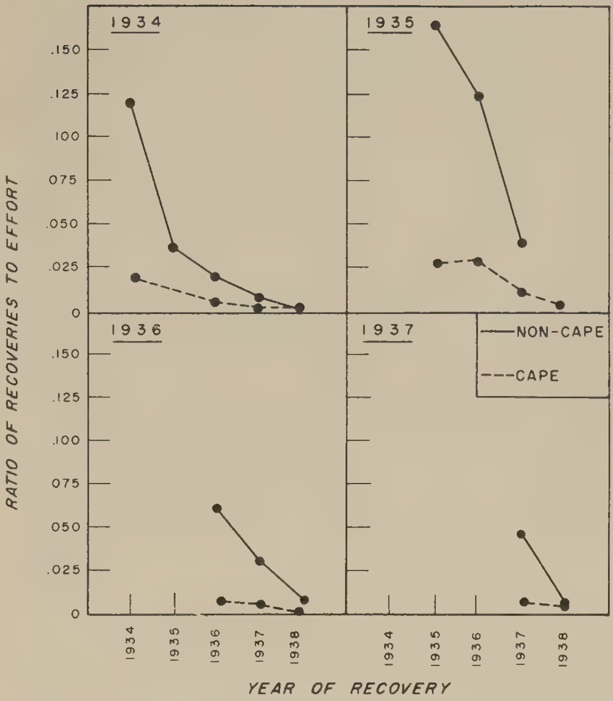


FIGURE 4.—Craig tagging experiments: the ratio of tag recoveries to effort in the Cape and non-Cape areas.

Similarly, results of each Craig experiment show a higher vulnerability in the non-Cape area than the Cape area during the earlier years of recovery, but the difference decreases in the later recovery years of each tagging. The ratio of recoveries to the catch in each area exhibits the same phenomenon.

Individual examination of either Sitka or Craig experiments would perhaps suggest that the change of vulnerability was due to a differential mortality rate in the two recovery areas. The change, how-

TABLE 4.—*Fishing effort and recoveries of Craig tagging experiments*

Year of tagging	Year of recovery	Cape area			Non-Cape area		
		Effort in ton-days *f*	Recoveries *R*	$\frac{R}{f}$	Effort in ton-days *f*	Recoveries *R*	$\frac{R}{f}$
1934	1934	3, 278	66	0. 0201	693	83	0. 1198
	1935	3, 065	37	. 0121	1, 200	46	. 0383
	1936	1, 604	9	. 0056	1, 005	21	. 0209
	1937	2, 147	3	. 0014	1, 743	14	. 0080
	1938	1, 294	2	. 0015	1, 136	1	. 0009
1935	1935	3, 065	84	. 0274	1, 200	199	. 1658
	1936	1, 604	49	. 0305	1, 005	126	. 1254
	1937	2, 147	27	. 0126	1, 743	70	. 0402
	1938	1, 294	8	. 0062	1, 136	0	0
1936	1936	1, 604	12	. 0075	1, 005	61	. 0607
	1937	2, 147	14	. 0065	1, 743	54	. 0310
	1938	1, 294	2	. 0015	1, 136	8	. 0070
1937	1937	2, 147	16	. 0075	1, 743	82	. 0470
	1938	1, 294	8	. 0062	1, 136	10	. 0088

ever, follows the same pattern in each series of experiments from both areas and rather indicates a movement and progressive mixing of fish between the Cape and non-Cape areas. This conclusion is based on the apparent rapid decrease of the vulnerability ratio in the area where tags were inserted as compared to the relatively slow change in the other recovery area.

After the 1934 and 1935 tagging, Dahlgren (1936) concluded that only "occasional migrants" from Sitka experiments mingled with fish in the non-Cape area and that there was "no counter migration" of the Craig stock to the Cape area. The vulnerability of tagged individuals during these 2 years indicates partial agreement with Dahlgren's findings. Subsequent recovery years (1936–39), however, indicate a more extensive and progressive mixing of the two stocks. This mixing may be the result of random dispersion or may be associated with definite migration patterns. To further examine the mixing phenomenon, the expected recoveries from equal effort in the two areas are compared.

SITKA EXPERIMENTS

Assuming that the proportion of recoveries to effort in the non-Cape area would not be significantly altered by a change in effort, the expected number of non-Cape recoveries can be calculated from effort equal to that of the Cape area. With this adjustment, a comparison of the vulnerability of tagged fish in the two areas can be made—that is, the ratio of the non-Cape recoveries to the total recoveries, Cape and non-Cape (fig. 5). The ratio increases with each year of tagging until 1938 when a decrease is recorded. The increase indicates a greater proportion of tags available in the non-Cape area from one year to the next. The phenomenon points again to migration from the Cape area. The successively higher ratio of non-Cape recoveries to total recoveries is also noted in the initial recovery year of the four experiments. The 1938 decrease suggests a reversal of the 1934–37 trend.

CRAIG EXPERIMENTS

Again adjusting to equal effort, the ratios of Cape recoveries to the total recoveries from Craig experiments do not show as concise a trend as the Sitka experiments (fig. 6). The ratios from 1934 through 1937 fall within the same general range of 0.10 to 0.25. Apparently, the migration of Craig stocks to the Cape area during this period is considerably less and more consistent than the migration of Sitka stocks to the non-Cape areas. The 1938 data indicate that individuals tagged in the Cape and which had migrated to the non-Cape area, apparently returned en masse to the Cape area. An explanation is not apparent, but the phenomenon may indicate that migration patterns are indeed flexible.

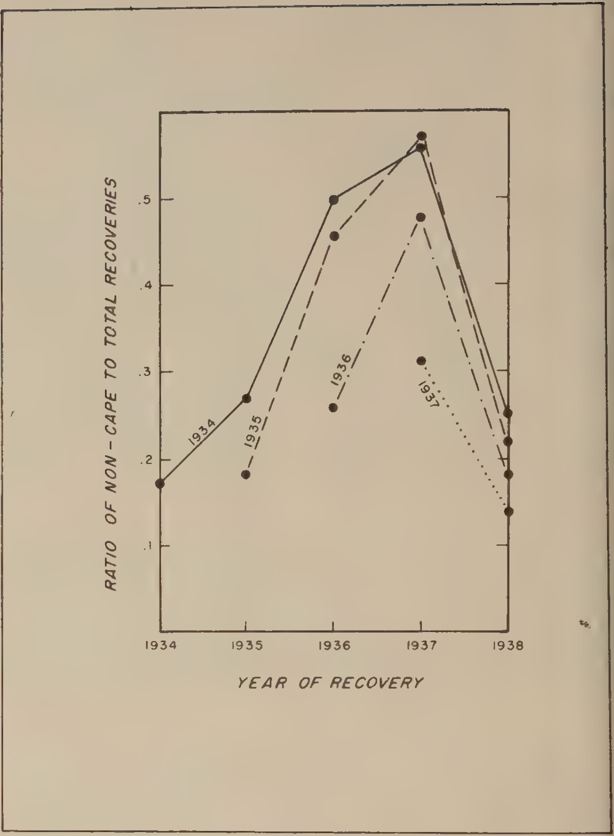
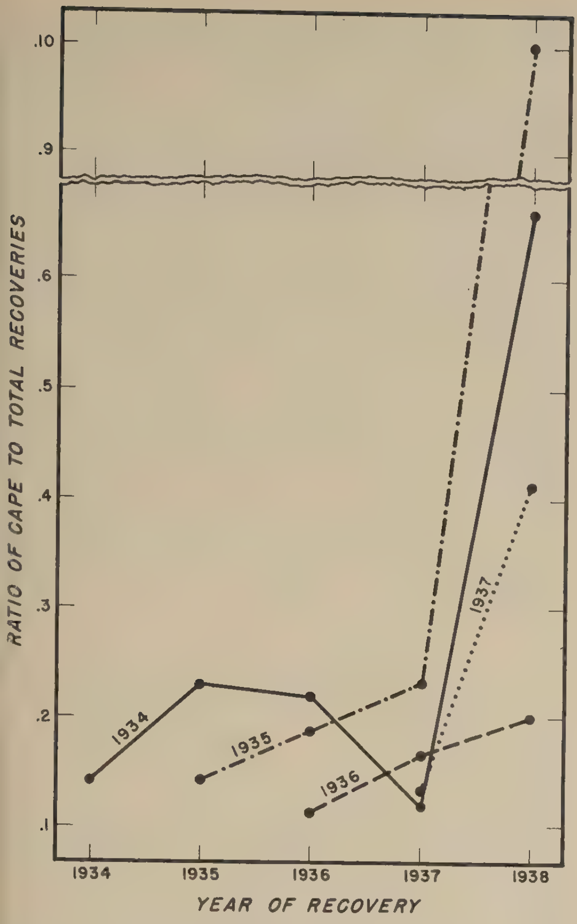


FIGURE 5.—Sitka tagging experiments: ratio of non-Cape to total recoveries.

In view of the intermingling between the two stocks, there is some question as to the validity of the Cape and non-Cape divisions for purposes of managing the fishery. Verification of the extent of intermingling is essential to the proper management of the fishery. Management practices have been based on the existence of independent populations and regulatory measures were instituted accordingly. If the mixing of the two stocks, Sitka and Craig, is extensive and consistent, the management concepts should be altered accordingly. For example, the recovery data



IGURE 6.—Craig tagging experiments: ratio of Cape to total recoveries.

ables 1 and 2) show considerable mixing of the vo stocks in the vicinity of Kuiu and Warren slands, and the allocation of these islands to the on-Cape area is not justified.

The conclusions of racial studies by Rounsefell nd Dahlgren (1935) do not support the hypothe-s of mixing derived from the tagging data. The uthors, however, make this statement in their ummary (page 140)—

> . . . It must be borne in mind that where morphologi-l differences have not been shown we can only assume at the populations are the same, until such time as we otain evidence to the contrary. Such evidence may me from tagging experiments.

Ideally, comparisons of the two hypotheses ould utilize data from the same year classes ıt meristic counts and morphological measure-ents were not recorded during the years of gging. Re-examination of racial data for other ear classes (Rounsefell and Dahlgren, 1935) does provide some evidence in support of intermingling between the Cape and non-Cape areas. The information presented cannot be conclusively credited to mixing, as there is a geographic progression of meristic characters and length of fish which may occur in response to environmental differences. This progression, however, does agree with expected results from mixing and should be noted. Mean vertebral counts from Cape Ommaney samples were higher than those from Craig, and mean counts from Warren and Noyes Islands (located between the Cape and Craig) were intermediate in value (see figure 1 for locations). The mean vertebral counts for the 1926 year class were: Cape, 52.423; Warren, 52.357; Noyes, 52.342; and Craig, 52.254. That the status of Warren Island samples was questioned is apparent in the statement of Rounsefell and Dahlgren (1935):

> Therefore the Warren Island samples must be regarded with some suspicion, especially as the proportion of the observed *z* forms of the calculated *z* is larger in the Warren Island samples than in those from other localities.

Length-frequency data listed by these authors for the 1926 and 1927 year classes show a comparable progression, the size of fish from Warren Island being intermediate to those from Noyes Island and Cape Ommaney (fig. 7). Rounsefell and Dahlgren (1935) made the following statement (page 133) about fish size which also can be explained on the basis of mixing.

> To gain an insight into the growth increments during the summer months the data have been grouped by 10-day periods. (See table 8). For Larch Bay 5-year-olds (herring in their fifth summer) taken during 1930, a consecutive series of eight periods shows no consistent changes in length during the first five periods (from June 21 up to and including August 10). There is an abrupt increase in length, however, between the fifth and sixth periods, the fish of the last three periods averaging about a half centimeter greater in body length. Such a sudden increase in length can scarcely be ascribed to growth but is probably due to an influx of new schools of herring onto the fishing grounds.
>
> That such a sudden change in body length is not due to growth is supported by the Noyes Island data, in which both the 4- and 5-year-olds taken during the last of June, the largest difference, that between the 5-year-olds, being 6 millimeters.

The tagging results coupled with the morphometric inconsistencies, which can be explained by mixing, favor the acceptance of stock intermingling

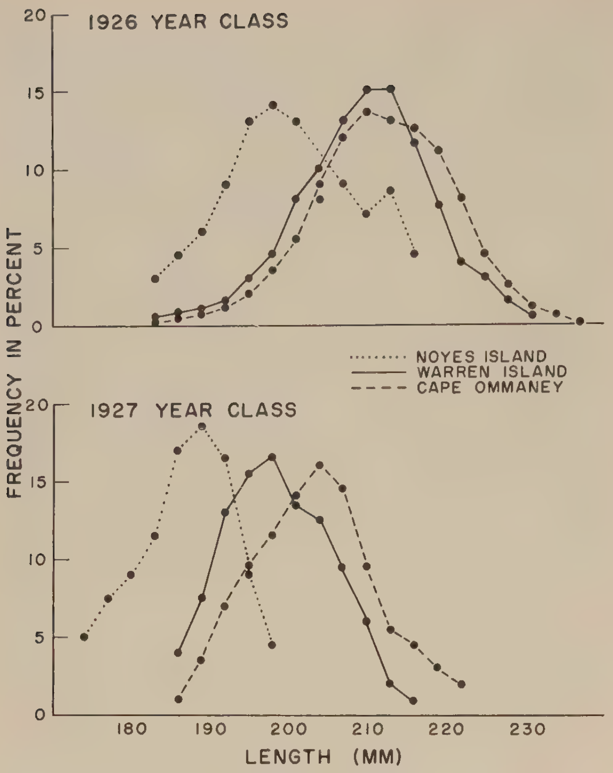


FIGURE 7.—Length-frequency distribution of two year classes taken in 1930 (Data from Rounsefell and Dahlgren, 1935.)

rather than a theory of discrete populations within the Cape and non-Cape areas.

MORTALITY ESTIMATES

Delineation of the migration patterns and mixing areas can be determined generally by examining recovery data. Estimates of population parameters, however, necessitate the assurance that the data fulfill certain requirements and that the limitations be known. Other than the previously mentioned limitations regarding tag recovery, the following items are not accounted for in the data:

1. Proportion of each year's catch which was searched by the magnets.
2. Efficiency of the various magnet installations.
3. Efficiency of tag collection by reduction plant personnel.

The assumption is that the proportion of catch examined and efficiency of recovery varied slightly among the years of study.

To determine whether tagged individuals were distributed as untagged members of the population, the recoveries from each experiment can be compared to the catch of the year classes which were in the postrecruit stage at the time of tagging. Dahlgren and Kolloen (1944) estimated the numbers of herring taken from each year class from 1929 through 1938. These estimates were obtained on an annual basis from the total catch, percentage age contribution, and average weight at each age. To utilize these data, the first consideration is to determine the age at which the majority of fish are recruited to the fishery. After the method described by Tester (1955), the estimates of Dahlgren and Kolloen have been weighted to 10,000 fish per year and averaged to establish the age of recruitment (table 5). It is evident that recruitment continues during the 5th year of life in some years, but the major portion of recruitment is completed by the 4th year of life.

TABLE 5.—*Estimated numbers of herring by year of life, weighted to 10,000 fish per year*

Year of capture	Year of life								
	2	3	4	5	6	7	8	9	10+
1929	------	151	8, 913	461	220	119	99	9	29
1930	------	39	1, 797	7, 689	209	140	72	30	24
1931	------	1, 250	1, 020	2, 247	5, 125	258	20	60	20
1932	------	410	3, 817	1, 179	1, 217	2, 967	410	------	------
1933	------	319	960	2, 768	1, 279	1, 488	3, 185	------	------
1934	------	9	7, 684	439	859	399	479	131	------
1935	------	121	379	9, 070	309	70	51	------	------
1936	40	871	1, 403	839	6, 492	218	113	16	8
1937	210	4, 600	1, 832	679	462	2, 139	70	8	------
1938	------	2, 090	6, 125	466	289	257	740	16	16
Total	250	9, 860	33, 930	25, 837	16, 461	8, 055	5, 239	270	97
Average	25	986	3, 393	2, 584	1, 646	805	524	27	10

The catch estimates by Dahlgren and Kolloen (1944) for the tagging and recovery period are based on Cape catches, but from the evidence in the previous section on intermingling, their data are considered representative of both Cape and non-Cape for this analysis (table 6). Further, the age composition of the catch is considered representative of the population at time of tagging. In each year of capture, the number of fish taken during the 4th year of life is underscored in table 6 with a solid line and the year classes below this line are not considered members of the population at time of tagging. (Unpublished data of several workers indicate that although some southeastern Alaska herring enter the summer fishery during their 3d year of life, relatively few of them are

BLE 6.—*Estimated catch of herring from each year class in millions of fish* [1]

Year class	Year of capture					Total by year class
	1934	1935	1936	1937	1938	
6	5.5					6
7	20.2		0.1			20
8	16.8	1.3	0.2			18
9	36.2	1.8	1.4	0.2	0.1	40
0	18.5	7.9	2.7	1.8	0.1	31
	323.8	232.2	80.5	55.1	4.6	696
2	.04	9.7	10.4	11.9	1.6	34
3		3.1	17.4	17.5	1.8	40
4			10.8	47.2	2.9	61
5			0.5	118.5	38.1	157
6				5.4	13.0	18

[1] The number of fish taken from the original population during the tagging r is determined by adding the number of individuals in the 4th year of and older.

ature the previous spring.) The total number fish taken from the original population during e tagging year is determined by adding the mber of individuals in the 4th year of life and der. The number of fish taken from the same pulation the following year is obtained by add- the number of individuals in the 5th year and der. Thus, the figures above the dotted lines table 6 are added to determine the numbers ptured from the initial population of each tag- g experiment in a given year of fishing.

The number of fish removed each year from each tagging population is compared with recoveries of tagged individuals from the same population (table 7). The recoveries are the total for each year of tagging and recovery as shown in table 1. The recoveries from each tagging experiment can now be compared with the catch in the several recovery years from each experiment. To analyze the results of each tagging year and of subsequent recoveries, the ratio of each year's recovery to the previous year's recovery and the ratio of each year's catch to the previous year's catch are determined (fig. 8). As shown in the scatter diagram, an increase in the catch ratio, C_i/C_{i-1}, is generally reflected by an increase in the recovery ratio, R_i/R_{i-1}. A *t*-test,

TABLE 7.—*Comparison of tagged individuals recovered and catch (in millions of fish) from initial tagging population*

Year of capture	Tagging year							
	1934		1935		1936		1937	
	Recoveries	Catch	Recoveries	Catch	Recoveries	Catch	Recoveries	Catch
1934	645	421						
1935	291	243	2,357	253				
1936	68	85	822	95	474	113		
1937	31	57	482	69	285	87	400	134
1938	7	5	51	6	26	8	51	11

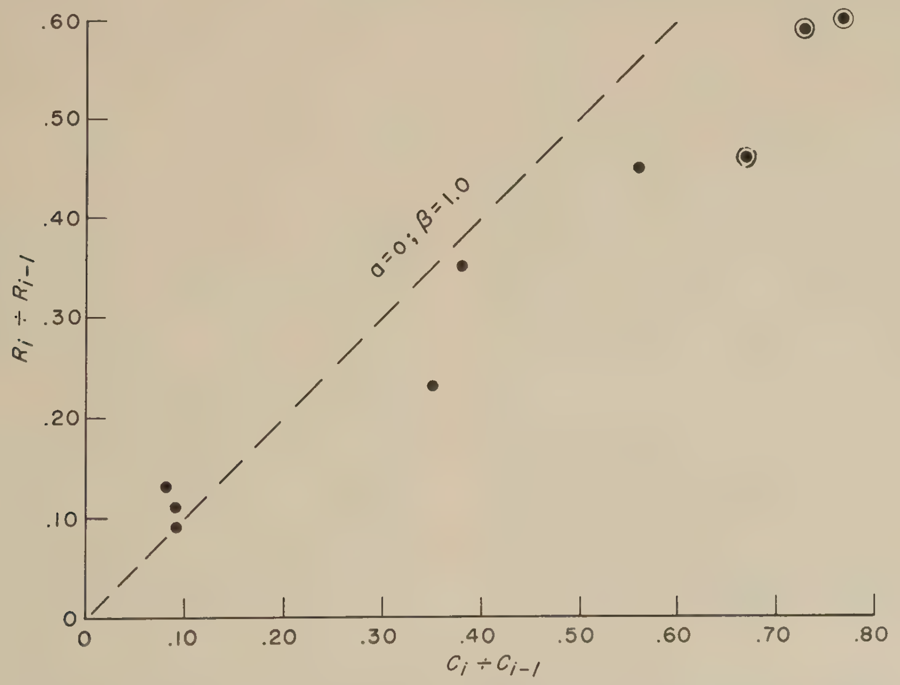


FIGURE 8.—Comparison of tag recoveries ratios (R_i/R_{i-1}) and commercial catch ratios (C_i/C_{i-1}), 1934–38. Circled dots represent data from the years 1936 and 1937.

however, indicates rejection of the hypothesis that the regression of the recovery ratios on catch ratios is 1.0. These results lead to the conclusion that the population of tagged fish is not distributed as the population(s) of untagged fish in the catch; however, further examination of the data reveals features which suggest that this conclusion should be qualified.

The catch ratios generally exceed the recovery ratio, and, presumably, this difference might account for losses caused by tagging mortality, lost tags, inadequacies of the recovery method, or immigration of fishes from other than the original tagging population. That immigration is an important consideration is evidenced by the following exercise. By subtracting the recoveries of non-Cape experiments from the total recoveries (table 7), the regression of catch ratio and recovery ratio deviates further from the hypothetical 1: 1. This indicates that fish of non-Cape origin emigrate and contribute to catches in the Cape area and that non-Cape tagging experiments must be included to validate the comparison. Immigration from populations of unknown origin is also considered plausible, and the 1936–37 catch data may reflect such a phenomenon. This ratio, C_{37}/C_{36}, is suspiciously higher than any of the other catch ratios in the three tagging experiments in which it is represented. When these three ratios (circled in figure 8) are omitted from the calculation of the regression, the "*t*-test" indicates that a regression of 0.95 is not rejected. Considering the limitations of the recovery data, coupled with the limitations of the catch estimates, it is perhaps surprising that the regression is as close to 1.0 as shown. With this evidence, the assumption is made that differences in the distribution of tagged and untagged fish are not sufficiently great to negate a comparison of recovery and catch data.

Estimates of mortality rates from the tagging data are influenced by the limitations listed in the previous section. Because of these limitations, specific values of population parameters are open to question. Nevertheless, the estimates are considered useful in determining the comparative success of the several experiments and the differences in mortality of the Sitka and Craig stocks.

The following equation was selected as most suitable for the data, and calculations of mortality for each year of the Sitka and Craig experiments are derived by this method.[1] The symbols utilized are essentially those of Ricker (1948 and 1958).

The reader will note that fishing effort is assumed proportional to the rate of exploitation. Justification of this assumption is discussed in the appendix which includes excerpts from a letter (dated March 18, 1958) from R. A. Fredin.

The equation:

$$\frac{R_t}{R_{t-1}}=\frac{Nk[1-(u_{t-1}+v_{t-1})]\,\frac{f_t}{f_{t-1}}\,u_{t-1}}{Nk\,u_{t-1}}$$

$$\frac{R_t}{R_{t-1}}=[1-(u_{t-1}+v_{t-1})]\,\frac{f_t}{f_{t-1}}$$

where:

$(u_{t-1}+v_{t-1}) = a =$ Annual rate of mortality[2]
$N =$ Number of fish tagged
$k =$ Tagging mortality
$R =$ Recoveries
$u =$ Exploitation rate
$v =$ Natural death rate[2]
$f =$ Effort

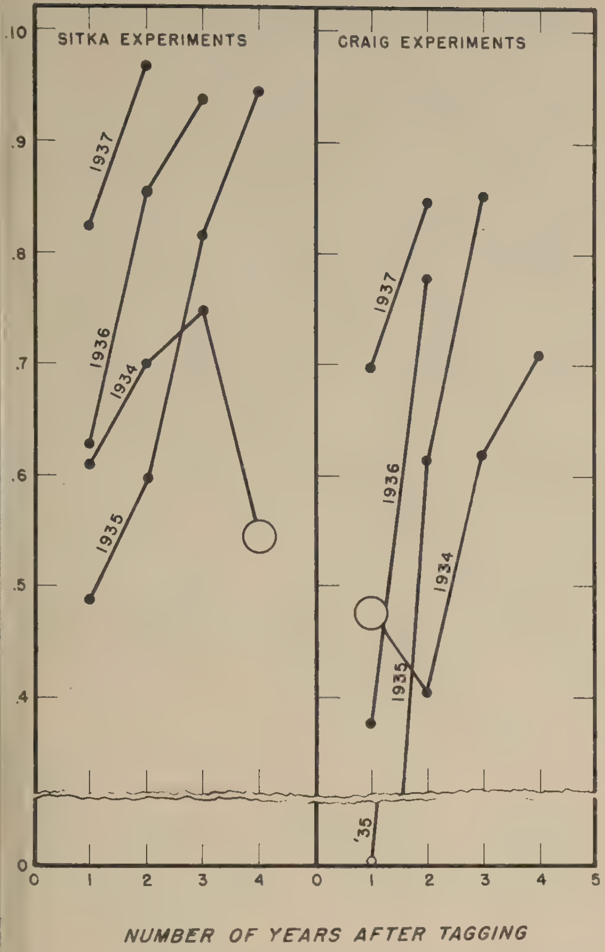
The results of these analyses provide the calculated "*a*" for successive tagging experiments at both Sitka and Craig (fig. 9). A point located on a given year expresses the rate of mortality from the previous year to the given year. The two rates circled on the graphs are presumed aberrant but do not materially influence the trend established by the remaining points. The comparison is concerned with the trend of a given experiment as well as the results between successive experiments. The results show:

1. In a given experiment, the mortality increases with each year of recovery. The two exceptions are circled on the graphs.
2. Between experiments, the later tagging exhibits a progressively higher rate of mortality in the initial and subsequent recovery years. An exception to this progression occurs in the Sitka

---

[1] The selection of an equation suitable for providing estimates of mortality rates created a number of problems, and in seeking advice, the author seldom found agreement among the critics as to the appropriate choice. Most individuals agreed, however, that mortality estimates should be presented and were necessary as comparative indexes for studying the tagging results. Of the different approaches tested, each either had characteristics which were not applicable or necessitated assumptions which the data could not meet. Comments from the reader regarding the treatment of the data will be welcomed.

[2] See Discussion section for comments on the definition of terms *a* and *v*.



gure 9.—Annual total mortality rates by year of recovery as determined from Sitka and Craig tagging experiments.

d Craig experiments of 1934. In some instances e mortality rates in the first and second recovery ars of this experiment exceed the mortalities licated in later experiments.

As effort did not increase, evidence of the ortality increase in the tagging experiments upled with the fact that the trend parallels e decline of the fishery suggests that the mor- ity increase was not spurious and represents actual biological change in the population.[3] amination of both fishing and natural mortality necessary to determine the causal factors of s trend.

Tester (1955) discusses a mortality increase with age in herring of British Columbia and the possibility of such an increase in the Alaska data should be considered. Ages of southeastern Alaska tagged herring were not determined, and the only means of checking the age composition of the tagged fish recovered would have been from the catches of the commercial fishery. However, this assumes that age groups in the commercial fishery are comparable to age groups on the spawning grounds where the fish were tagged. Field work undertaken by the author in 1956 provides a comparison of age groups from the summer fishery and the bait fishery—the latter being conducted on the Sitka spawning grounds (fig. 10). The age composition of the two groups, as determined from scales, does compare favorably and suggests the assumption is not unreasonable.

The data of Dahlgren and Kolloen (1944) in table 6 are utilized to calculate the percentage age composition during the years of tagging (fig. 11). As mentioned earlier in this section, fish in their 3d year of life in the summer fishery are not considered members of the previous spring's spawning population, and the percentage age composition presented includes only fish in their 4th year and older. The age composition during

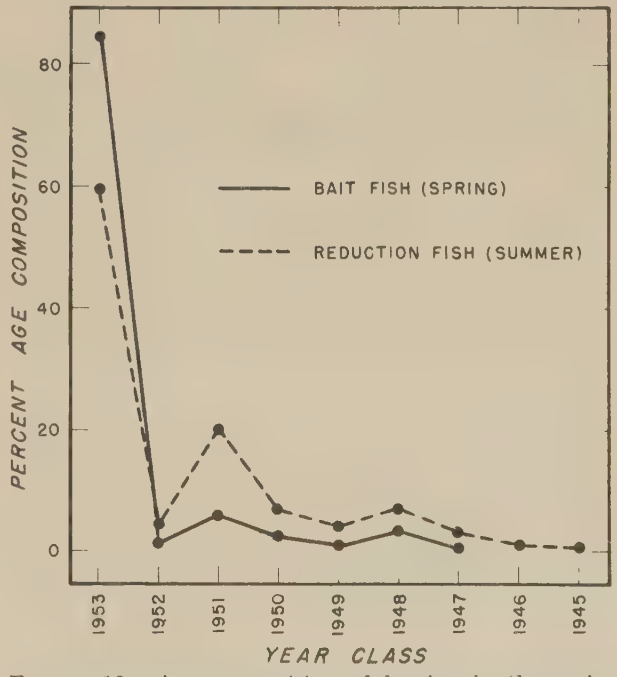


Figure 10.—Age composition of herring in the spring and summer fishery in southeastern Alaska.

Catches in 1934 and 1935 averaged 120 million pounds per year, whereas hes in 1936 and 1937 averaged 85 million pounds, and in 1938 and 1939, than 50 million pounds per year (Skud, Sakuda, and Reid, 1960).

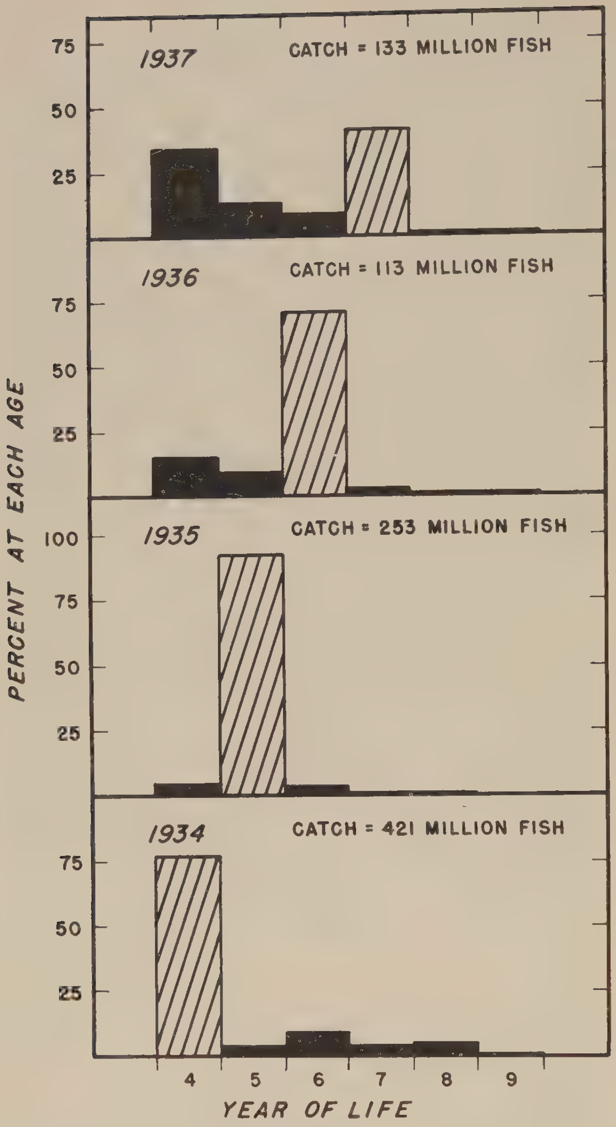


Figure 11.—Age composition of the catch in the summer fishery, 1934–37.

this period is dominated by the 1931 year class. In 1934, 1935, and 1936, this year class, represented by fish in their 4th, 5th, and 6th year of life, respectively, annually accounted for more than 70 percent of the total age composition. As fish in their 7th year, the contribution of the 1931 year class approximated 40 percent and was still dominant. In essence, the tagging experiments must have been concentrated on a single year class, 1931, and analyses of recovery data should reflect this phenomenon.

If we consider that the major portion of the tagging was carried out on a single year class and that the catch generally declined during this period, reexamination of figure 9 indicates an apparent mortality increase with age. That is, the earlier experiments carried out with younger fish exhibited a lower mortality than later experiments with older fish. From Sitka recoveries, calculations of mortality rates assigned to year of capture represent mortality between successive ages of the year class (fig. 12). Again, as in figure 9, the trend depicted by the 1935, 1936, and 1937 experiments is disrupted by the 1934 tagging experiment. Other than the 1934 experiment, an increased mortality with age is indicated. One difference in the 1934 experiment which may have influenced returns of tags is the heavy recruitment of the 1931 year class that occurred after the 1934 tagging.

Figure 5, which shows that the availability of Sitka tags in the non-Cape area generally increases with time, suggests that the movement of herring also may be associated with age.

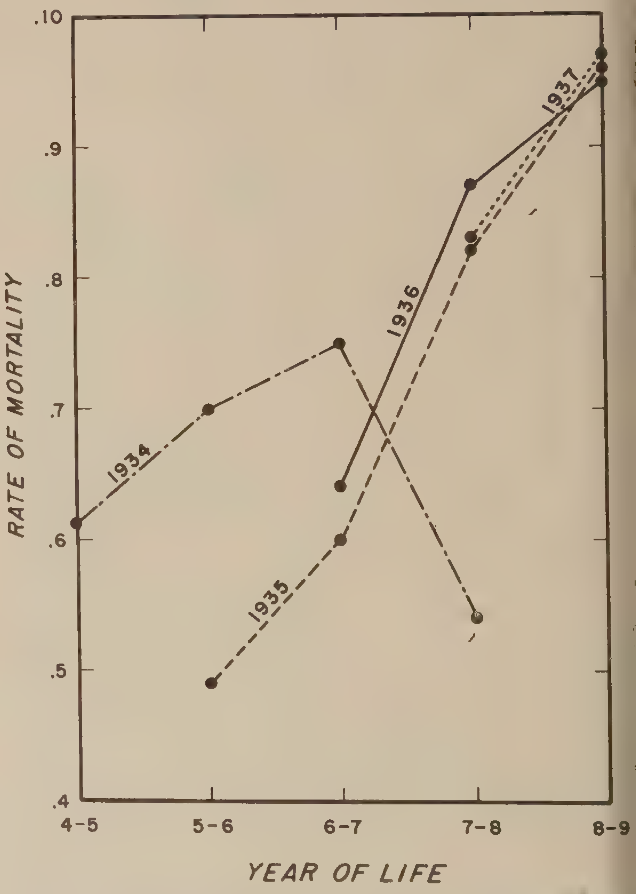


Figure 12.—Annual total mortality between ages as determined from Sitka experiments.

DISCUSSION AND CONCLUSIONS

esults of these tagging experiments indicate the definition of a, total mortality, should ude those losses which result from the emi- ion of individuals from the fishing area. definition of v, natural mortality, lacks the notation of losses other than natural deaths. erton and Holt (1957) using terms F and X ent the necessary refinements for a tagging y. That is, F is the coefficient of reduction arks due to fishing and X the sum of all other es which reduce marks—natural deaths, ing mortality, emigration, etc.

stimates of population parameters based on recovery of tagged individuals require that ain established criteria be fulfilled. The ibility of realizing such fulfillment in natural lations is slight. In this study, various mptions regarding recoveries were necessary n precise data were lacking. Some of these mptions have little factual support but have a minor consequence in the analyses. The ibution of tagged fish and the efficiency of very, however, are factors of major conse- ice. A comparison of recovery data and n data supported the assumption that tagged untagged individuals were equally vulnerable apture and that efficiency of recovery varied ittle from year to year.

ne conclusions from this report are:

Intermingling between Sitka and Craig stocks more extensive than previously indicated was centered in the vicinity of Kuiu Island Warren Island.

Because of this intermingling, Cape and non- e divisions of the fishing grounds cannot be idered distinct in regard to management of ommercial fishery.

The 1931 year class dominated the age position in the summer fishery during each ing year, 1934–37.

An increase in natural mortality with age indicated.

hether or not these conclusions are valid in the ent day fishery is not known, but they most inly should be investigated, and the following estions should be considered in any future ing experiments:

Design the experiment to further test the ee of intermingling between Sitka and Craig ks.

2. Conduct summer as well as spring tagging to determine if fish return to the same spawning beaches after mixing on the fishery grounds.
3. Age tagged individuals to: (a) relate intermingling with age, (b) determine variations in recovery of age groups, (c) provide more precise estimates of mortality.
4. Assess recovery methods to: (a) determine portion of catch examined, (b) test efficiency of recovery at each plant.
5. Conduct tagging experiments in other areas to determine the degree of emigration and immigration of fish in this fishery.

ACKNOWLEDGMENTS

I did not participate in either the original field work or in compiling the original data presented in this report and I wish to acknowledge the thorough work of former investigators. The initial tagging experiments reported by Rounsefell and Dahlgren (1933 and 1935) and Dahlgren, (1936) included a comprehensive review of tagging results through 1935. Subsequent experiments were supervised by Dahlgren and the late L. N. Kolloen. The success of their early work is evidenced by the rather wide acceptance of the tagging procedures in both Canadian and European herring investigations. The author is indebted to each of these men, particularly George A. Rounsefell who suggested preparing this report and commented on the original manuscript. The author also wishes to acknowledge the comments of Reynold A. Fredin, Basil B. Parrish, William E. Ricker, and the late Clyde C. Taylor.

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APPENDIX

Excerpts from letter by R. A. Fredin (March 18, 1958):

Fishing effort is assumed to be proportional to rate of exploitation in the model (see appendix). The following indicates the amount of error introduced by this assumption when fishing effort is proportional to the instantaneous rate of fishing. The rate of exploitation is given by the equation

$$u=\frac{pa}{i}$$

when

$$a=1-e^{-(p+q)}$$

$$p+q=i$$

$$p=kf$$

k being a constant of catchability and f being the units of fishing effort.

The rate of change of u with respect to p (or f, since p is proportional to effort) is as follows:

$$\frac{\Delta u}{\Delta p}=\frac{i\frac{\Delta pa}{\Delta p}-pa\frac{\Delta i}{\Delta p}}{i^2}$$

$$\frac{\Delta pa}{\Delta p}=p\frac{\Delta a}{\Delta p}+a\frac{\Delta p}{\Delta p}$$

$$\frac{\Delta a}{\Delta p}=\frac{\Delta[1-e^{-(p+q)}]}{\Delta p}=e^{-(p+q)}$$

$$\frac{\Delta p}{\Delta p}=1$$

$$\frac{\Delta pa}{\Delta p}=pe^{-(p+q)}+a$$

$$\frac{\Delta i}{\Delta p}=\frac{\Delta(p+q)}{\Delta p}=1$$

$$\frac{\Delta u}{\Delta p}=\frac{i[pe^{-(p+q)}+a]-pa}{i^2}$$

$$=\frac{ipe^{-(p+q)}+(i-p)a}{i^2}$$

Two tables were constructed, one using p-values ranging from 0.05 to 1.90 with a q-value (natural mortality rate) of 0.1, the other using p-values ranging from 0.05 to 1.70 with a q-value of 0.3. When values for $\Delta u/\Delta p$ are plotted against p, the slope of the curve is found to be changing and not constant, which it would be if u was proportional to f. However, within a limited range of p, the error caused by a changing slope is not too great.

Using effort data from your manuscript and assigning values of k (catchability) ranging from 0.0001 to 0.0004 to the effort data and selecting q-values of 0.1 and 0.3, "true" u and estimated u-values were calculated and compared. The results show that at low fishing mortality rates (where $k=0.0001$) the difference between the "true" and estimated u-values is insignificant, less than 0.01. As the fishing rate increases (i.e., at higher k-values) the error increases up to about 0.10 in some years.

MODEL OF THE MIGRATION OF ALBACORE IN THE NORTH PACIFIC OCEAN

By Tamio Otsu and Richard N. Uchida, *Fishery Biologists*
Bureau of Commercial Fisheries

ABSTRACT

n the basis of tag recovery data, age and growth in-
mation, and distribution and size frequency data
n the various fisheries, a model of the migration of
acore in the North Pacific Ocean has been developed.
s model is consistent with the hypothesis that there
single population of albacore in the North Pacific
an.

he model depicts extensive migrations of the alba-
e from one fishery to another and from one side of
North Pacific to the other side. In general it is
wn that albacore recruitment into the commercial
eries takes place largely in the eastern Pacific, and
t there is a greater volume of migration of the com-
rcial sizes of fish in the westerly direction from the
erican fishery into the Japanese fisheries, than vice
a. There is a tendency for the youngest fish in the
erican fishery to return to the same fishery the fol-
ing season rather than to migrate across into the
Japanese fisheries. This tendency is reduced in the older fish. Some albacore may be available to the American fishery for as many as four or five successive seasons.

As the albacore attain sexual maturity in temperate waters (6-year-olds and older) they move south into subtropical waters, where they make up the reproductive unit of the North Pacific population. This movement south takes place in the spring at the end of the Japanese winter longline season. It is hypothesized that spawning occurs in subtropical waters during the summer, and that the larval and early juvenile stages are spent in these waters. When about 1 year old, the fish migrate into temperate waters, but do not immediately join the exploited stock. The albacore are generally not available to the commercial fisheries until they are 2 or 3 years old.

n the basis of tag recovery data, age and
wth information, and distribution and size fre-
ncy data from the various fisheries, a model
the migration of the albacore, *Thunnus germo*
cépède), in the North Pacific Ocean is pro-
ed. This model is consistent with the hypoth-
that there is a single population of albacore
he North Pacific and that the North Pacific
acore fisheries, both American and Japanese,
exploiting a common resource. The model is
sented with the hope that critical examination
and testing of it may lead to a better understanding of the albacore resource of the North Pacific Ocean.[1]

NORTH PACIFIC ALBACORE FISHERIES

The three major albacore fisheries in the North Pacific are: (1) The Japanese livebait fishery during April–July off the coast of Japan (Van Campen, 1960); (2) the Japanese longline fishery during October–March from the coast of Japan east to about longitude 170° W. (Nankai Regional Fisheries Research Laboratory, 1954); and (3) the U.S. west coast trolling and livebait fishery during June–November between Baja California and the Pacific Northwest (Clemens, 1955). The

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TE.—Approved for publication January 18, 1962.

[1] recent publication by Clemens, Harold B. (1961) ("The Migration,
and Growth of Pacific Albacore (*Thunnus germo*), 1951–1958." Califor-
Department of Fish and Game, Fish Bulletin 115, 128 pp.) carries a dis-
on on the same subject of oceanwide migrations of the albacore.

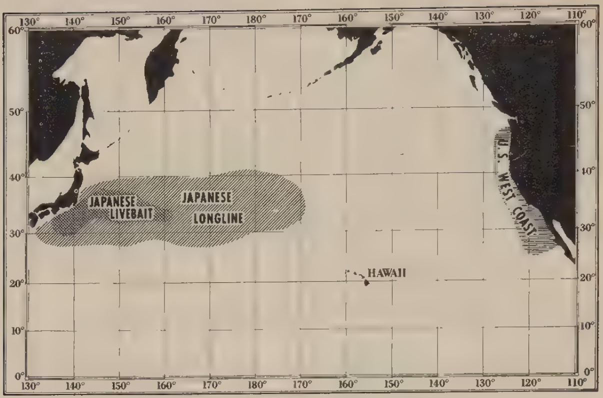


FIGURE 1.—The three major North Pacific fisheries for albacore.

general areas of the three fisheries are shown in figure 1.

SEASONAL DISTRIBUTION AND MOVEMENTS OF THE FISHING GROUNDS

The seasonal shifting of the fishing grounds within the Japanese livebait fishery (fig. 2), Japanese winter longline fishery (fig. 3), and the American west coast fishery (fig. 4) reflects the pattern of the albacore migration within these respective grounds. The Japanese livebait fishery begins off southern Japan in late April or May and gradually moves north and northeast. The fishery reaches its peak in June and rapidly declines in July, as the fish move farther offshore to the eastward.

The Japanese winter longline fishery begins in October, with its center of abundance located in midocean generally between 170° E. and 180° and along latitude 38° N. There is a gradual southwestward shift of the areas of highest catch rate (Nankai Regional Fisheries Research Laboratory 1959) which continues through March. There after the fishery declines very rapidly. Toward the end of the fishing season, in March, the cente of concentration shifts to around latitude 30° N longitude 140° E.

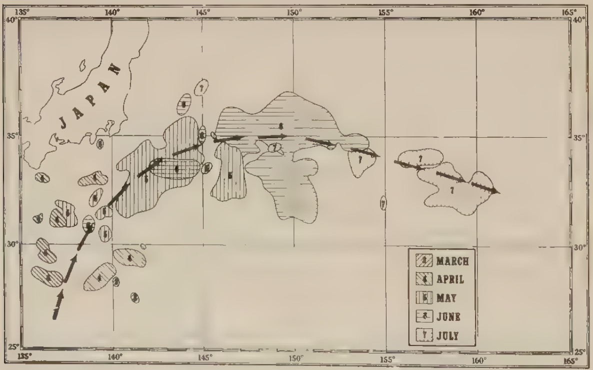


FIGURE 2.—Seasonal pattern of movement of the Japanese livebait fishery. (After Van Campen, 1960, fig. 2.) (The general direction of movement is indicated by the arrow.)

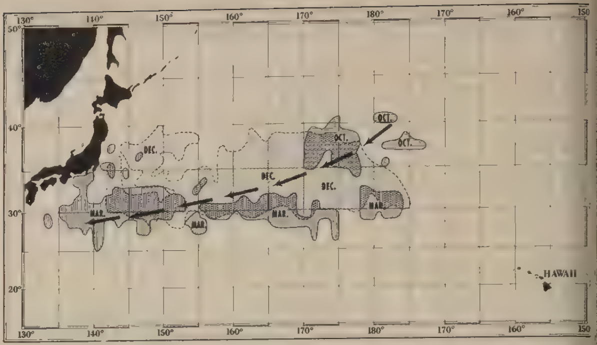


FIGURE 3.—Seasonal pattern of movement of the Japane winter longline fishery, as constructed from data of t Nankai Regional Fisheries Research Laboratory (1959 (The general direction of movement is indicated by t arrow.)

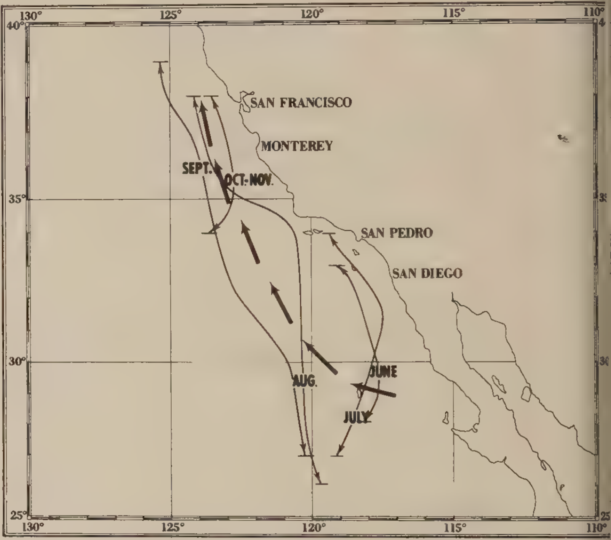


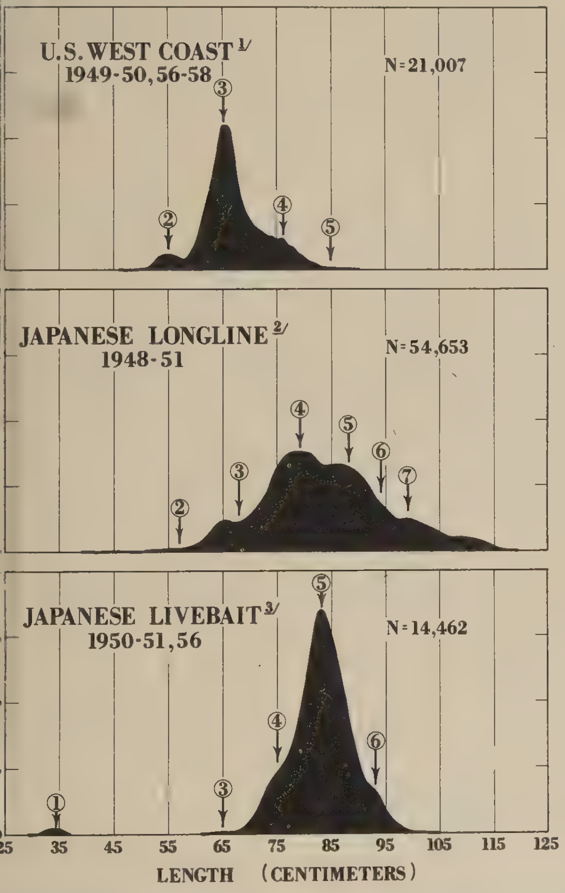
FIGURE 4.—Seasonal movement of the California albacor fishery in 1953. Each line extends over the total are fished during the month and describes diagrammaticall the northward expansion of the fishery as the seaso progresses. (From Clemens, 1955, fig. 24.) (The gen eral direction of movement is indicated by the arrow

The American fishery tends to move northwar along the coast as the season progresses (Clemens 1955). This tendency is indicated in figure 4 which is a partial reproduction of Clemens' figur 24.

SIZES AND ESTIMATED AGES OF FISH EXPLOITED

composite length frequency distribution for of the fisheries is shown in figure 5. The al lengths of the age groups are approxima- based on the appearance of the modes in the h frequency distributions, as well as on an core growth curve derived from tag recovery (Otsu, 1960).

udies to date have not yielded a satisfactory od for assigning absolute ages to the albacore. vth curves have been constructed (Otsu,), but the early growth, below the point of inflection on the curve, remains questionable. By means of a Gompertz equation, Otsu (1960) attempted to describe the entire growth curve of the albacore but concluded that the initial growth as shown by the resulting curve seemed unreasonably slow, since it required about 3 years for the fish to attain a weight of 1 pound (about 30 cm.). He suggested a possible error of 1 or 2 years in the ages assigned by this method.



npiled from Graham (1959); and from unpublished data of the Fish ssion of Oregon, California Department of Fish and Game, and the gton State Department of Fisheries.

npiled from data in Nankai Regional Fisheries Research Laboratory nd (1951).

np led from data in Nankai Regional Fisheries Research Laboratory nd Mie Prefectural Fisheries Experimental Station (1957).

RE 5.—Length frequency distributions of albacore en in the three major fisheries. (The ages (encircled) shown at the approximate modal size of each age up.)

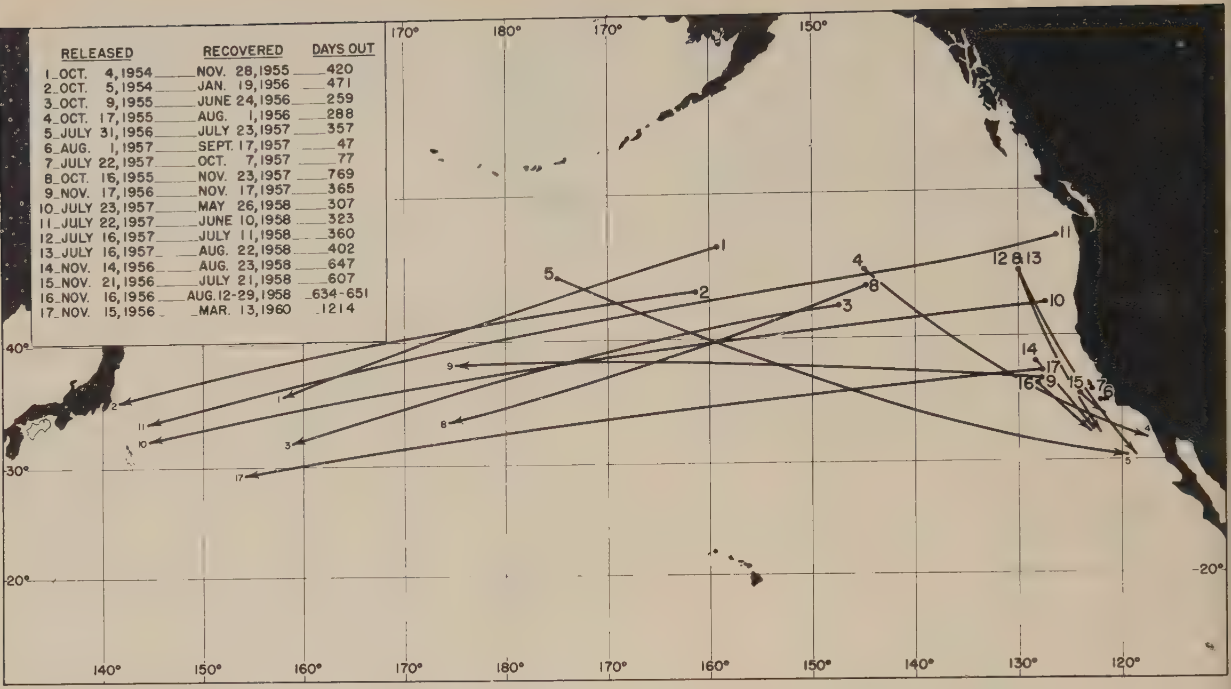
A group of 30–35 cm. fish occasionally enters the commercial catches. It is possible that these are the first-year fish, and assuming that they are, it is postulated that the albacore are about 2 years old when (at a length of about 50 cm.), they first enter the fisheries in significant numbers. On this assumption, the Japanese livebait fishery generally exploits three age groups, 4-, 5-, and 6-year-olds, whose modal lengths are approximately 75, 83, and 93 cm. Occasionally 1-year-old fish (around 35 cm.) are taken, but not in great numbers, and 2-year-olds are usually absent from the catches. Three-year-old fish appear in small numbers.

The winter longline fishery exploits a wide range of ages, from 2- to 8- or 9-year-old fish. Generally, the catches are composed of the following modal sizes, corresponding to the age groups within this range: 57, 68, 79, 88, 94, 99 cm., and a few fish of larger groups. Most abundant are the 4- and 5-year-old fish (79- and 88-cm. groups).

The American fishery is generally based on three groups, which are approximately 2-, 3-, and 4-year-old fish (55, 65, and 76 cm.), but small numbers of older groups (5- and 6-year-olds) also appear. The 3-year-old fish are usually the most abundant in the catches. Aside from the infrequent occurrence of 1-year-old fish in the Japanese livebait fishery, the youngest members of the albacore population are exploited by the American fishery since here, for the first time, 2- and 3-year-old fish appear in significant quantities.

MIGRATION OF ALBACORE BETWEEN FISHERIES

Until recently little was known of the distribution of albacore in the approximately 2,000 miles of open ocean between the Japanese winter longline grounds and the west coast of North America. Since 1954, the Bureau of Commercial Fisheries Biological Laboratory, Honolulu, has conducted 10 exploratory fishing and 6 hydro-



RELEASED	RECOVERED	DAYS OUT
1_OCT. 4, 1954	NOV. 28, 1955	420
2_OCT. 5, 1954	JAN. 19, 1956	471
3_OCT. 9, 1955	JUNE 24, 1956	259
4_OCT. 17, 1955	AUG. 1, 1956	288
5_JULY 31, 1956	JULY 23, 1957	357
6_AUG. 1, 1957	SEPT. 17, 1957	47
7_JULY 22, 1957	OCT. 7, 1957	77
8_OCT. 16, 1955	NOV. 23, 1957	769
9_NOV. 17, 1956	NOV. 17, 1957	365
10_JULY 23, 1957	MAY 26, 1958	307
11_JULY 22, 1957	JUNE 10, 1958	323
12_JULY 16, 1957	JULY 11, 1958	360
13_JULY 16, 1957	AUG. 22, 1958	402
14_NOV. 14, 1956	AUG. 23, 1958	647
15_NOV. 21, 1956	JULY 21, 1958	607
16_NOV. 16, 1956	AUG. 12-29, 1958	634-651
17_NOV. 15, 1956	MAR. 13, 1960	1214

FIGURE 6.—Net movements of albacore tagged by the Bureau of Commercial Fisheries Biological Laboratory, Honolulu. (The lines connect the points of release and recovery of each fish, and the numbers correspond to the "Recovery Number" in table 1).

graphic cruises in that area. The results of these cruises are described by Shomura and Otsu (1956), Graham (1957), and Graham (MS).[2] By longlining, trolling, and gillnetting, it was shown that albacore are generally scarce in this extensive area during the winter and spring. In summer, the surveys disclosed localized areas of abundance between longitudes 160° W. and 175° W., but farther to the east albacore occurrence was sparse. In the fall, the catches indicated a continuous distribution of fish, although not in great abundance, between the declining American fishery and the developing Japanese longline fishery.

The migration of the albacore between the west coast of the United States and the Pacific coast of Japan has been shown in the results of tagging experiments (Otsu, 1960). Data on the size and age composition of fish exploited in the different fisheries provide supplementary evidence on the migrations of albacore among the areas of the North Pacific fisheries.

The Bureau of Commercial Fisheries Biological Laboratory, Honolulu, tagged a total of 934 albacore between January 1954 and September 1958 in the temperate North Pacific between the U.S. west coast and longitude 179° E. (Otsu, 1960). In addition, 270 albacore were tagged in the Japanese livebait fishing grounds in the spring of 1956 (Van Campen and Murphy, 1957). Of the 934 releases in the central and eastern North Pacific, 17 recoveries (1.8 percent) had been reported as of August 1961 (table 1 and fig. 6). To date no recoveries have been made of the 270 fish tagged in the Japanese fishery.

Recoveries of albacore tagged by other research agencies (nine by the Nankai Regional Fisheries Research Laboratory, five by the California Department of Fish and Game, and four by the Fish Commission of Oregon) are listed in table 2 and illustrated in figure 7.

Tag recoveries have shown transpacific movements of fish from the American fishery into the Japanese longline fishery (fig. 6 Nos. 9 and 17; fig. 7, Nos. 19, 20, and 21) and into the Japanese livebait fishery (fig. 6, Nos. 10 and 11; fig. 7, Nos. 18, 22, 23, and 33). There have been movements from the midocean area between the American fishery and the Japanese longline fishery into the American fishery (fig. 6, Nos. 4 and 5), as well as into both Japanese fisheries (fig. 6, Nos. 1, 2, 3,

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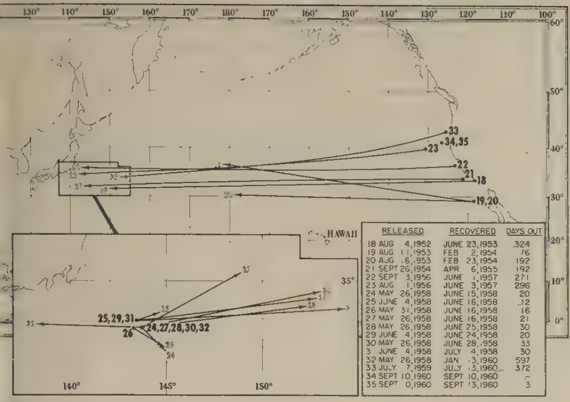
[2] Graham, Joseph J., Manuscript. The macroecology of the albacore tuna, *Thunnus germo* (Lacépède), in the central North Pacific. Bureau of Commercial Fisheries Biological Laboratory, Honolulu.


130°
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120°
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100°
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10°
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33
34,35
23
22
21
18
19,20
HAWAII
35°
25,29,31
26
24,27,28,30,32
140°
145°
150°
RELEASED
RECOVERED
DAYS OUT
18 AUG 4,1952 JUNE 23,1953 .324
19 AUG 11,1953 FEB 2,1954 76
20 AUG 6,1953 FEB 23,1954 192
21 SEPT 26,1954 APR 6,1955 192
22 SEPT 3,1956 JUNE 1,1957 271
23 AUG 1,1956 JUNE 3,1957 296
24 MAY 26,1958 JUNE 15,1958 20
25 JUNE 4,1958 JUNE 16,1958 12
26 MAY 31,1958 JUNE 16,1958 16
27 MAY 26,1958 JUNE 16,1958 21
28 MAY 26,1958 JUNE 25,1958 30
29 JUNE 4,1958 JUNE 24,1958 20
30 MAY 26,1958 JUNE 28,1958 33
3 JUNE 4,1958 JULY 4,1958 30
32 MAY 26,1958 JAN 3,1960 597
33 JULY 7,1959 JULY 3,1960 372
34 SEPT 10,1960 SEPT 10,1960 –
35 SEPT 0,1960 SEPT 13,1960 3

URE 7.—Net movements of albacore tagged by the ankai Regional Fisheries Research Laboratory, the alifornia Department of Fish and Game, and the Fish ommission of Oregon. (The lines connect the points f release and recovery of each fish, and the numbers orrespond to the "Recovery Number" in table 2).

and 8). Tagging in the Japanese livebait fishery has resulted in recaptures which showed a generally easterly movement away from Japan (fig. 7, Nos. 24–31), and one such recovery has been made in the winter longline fishery (fig. 7, No. 32). None of the albacore tagged in the Japanese livebait fishery has been retaken in the American fishery, but, as will be shown later, this probably does not mean that there is a complete lack of migration in that direction.

MODEL OF MIGRATION

Interpretation of the pattern of tag returns indicates that albacore undertake no more than one transpacific crossing during a 1-year period. These movements are considered to be rapid between the established fisheries, and slow within the areas of the fisheries.

TABLE 1.—*Recoveries of albacore tagged by the Bureau of Commercial Fisheries Biological Laboratory, Honolulu*

Recovery No.	Release		Recapture			
	Date	Fishing gear	Date	Fishermen	Vessel	Fishing gear
	Oct. 4, 1954	Longline	Nov. 28, 1955	Japanese	*No. 1 Seifuku Maru*	Longline.
	Oct. 5, 1954	Trolling	Jan. 19, 1956	do	unknown	Do.
	Oct. 9, 1955	do	June 24, 1956	do	*No. 6 Usa Maru*	Livebait.
	Oct. 17, 1955	do	Aug. 1, 1956	American	unknown	Trolling.
	July 31, 1956	do	July 23, 1957	do	*Carol Virginia*	Livebait.
	Aug. 1, 1957	do	Sept. 17, 1957	do	*Crisella*	Trolling.
	July 22, 1957	do	Oct. 7, 1957	do	*Mercator*	Livebait.
	Oct. 16, 1955	do	Nov. 23, 1957	Japanese	*No. 3 Hoju Maru*	Longline.
	Nov. 17, 1956	do	Nov. 17, 1957	do	unknown	Do.
	July 23, 1957	do	May 26, 1958	do	do	Livebait.
	July 22, 1957	do	June 10, 1958	do	*No. 2 Zenshin Maru*	Do.
	July 16, 1957	do	July 11, 1958	American	*Lococo Brothers*	Trolling.
	July 16, 1957	do	Aug. 22, 1958	do	*Bernard Pedro*	Do.
	Nov. 14, 1956	do	Aug. 23, 1958	do	*Paul C.*	Do.
	Nov. 21, 1956	do	July 21, 1958	do	*Mable*	Livebait.
	Nov. 16, 1956	do	Aug. 12–29 1958	do	*Daiho II*	Do.
	Nov. 15, 1956	do	Mar. 13, 1960	Japanese	*No. 2 Hayatori Maru*	Longline.

Recovery No.	Release			Recapture			
	Position		Size (cm.)	Position		Size (cm.)	Days out
	Latitude	Longitude		Latitude	Longitude		
	46°30′ N.	159°18′ W.	78.2	35°45′ N.	157°39′ E.		420
	43°31′ N.	161°16′ W.	68.0	35°23′ N.	141°20′ E.		471
	42°16′ N.	147°16′ W.	63.4	31°54′ N.	158°37′ E.		259
	44°55′ N.	144°48′ W.	59.9	31°21′ N.	117°17′ W.	72.3	288
	44°31′ N.	174°55′ W.	68.4	30°08′ N.	119°03′ W.	78.0	357
	34°49′ N.	121°57′ W.	66.5	34°49 N.	121°26′ W.		47
	35°43′ N.	122°58′ W.	65.5	36°24′ N.	123°07′ W.	67.0	77
	43°40′ N.	144°40′ W.	65.1	33°22′ N.	174°07′ E.	94.8	769
	36°44′ N.	127°37′ W.	85.2	38°08′ N.	174°53′ E.	97.5	365
	42°20′ N.	127°33′ W.	78.0	32°15′ N.	144°15′ E.	85.2	307
	47°00′ N.	126°18′ W.	75.0	33°40′ N.	144°00′ E.		323
	44°47′ N.	130°04′ W.	65.0	30° N.	118°45′ W.[1]	77.3	360
	44°47′ N.	130°04′ W.	75.0	32° N.	122° W.[1]	84.5	402
	38°00′ N.	128°25′ W.	79.4	32°15′ N.	122°30′ W.	92.6	647
	35°21′ N.	123°57′ W.	68.6	34°00′ N.	122°10′ W.	86.4	607
	36°48′ N.	127°33′ W.	65.9	32°38′ N.	123°00′ W.	81.2	634–651
	37°12′ N.	127°41′ W.	60.8	29°28′ N.	153°45′ E.	ca. 90	1,214

pproximate position of recapture.

Table 2.—*Recoveries of albacore tagged by the California Department of Fish and Game, the Fish Commission of Oregon and the Nankai Regional Fisheries Research Laboratory*

Recovery No.	Release			Recapture			
	Date	Agency [1]	Fishing gear	Date	Fishermen	Vessel	Fishing gea
18	Aug. 4, 1952	CFG [2]	Trolling	June 23, 1953	Japanese	*No. 5 Chosho Maru*	Livebait.
19	Aug. 11, 1953	CFG	do	Feb. 2, 1954	do	*No. 1 Konpira Maru*	Long line.
20	Aug. 16, 1953	CFG	do	Feb. 23, 1954	do	*Sin-o Maru*	Do.
21	Sept. 26, 1954	CFG	do	Apr. 6, 1955	do	*No. 5 Shoyei Maru*	Do.
22	Sept. 3, 1956	CFG	do	June 1, 1957	do	unknown	Livebait.
23	Aug. 11, 1956	OFC	do	June 3, 1957	do	do	Do.
24	May 26, 1958	NRFRL	Livebait	June 15, 1958	do	*No. 15 Hoko Maru*	Do.
25	June 4, 1958	NRFRL	do	June 16, 1958	do	*No. 3 Wasumi Maru*	Do.
26	May 31, 1958	NRFRL	do	June 16, 1958	do	*No. 7 Kyowa Maru*	Do.
27	May 26, 1958	NRFRL	do	June 16, 1958	do	*No. 8 Fukuichi Maru*	Do.
28	May 26, 1958	NRFRL	do	June 25, 1958	do	*Chiyo Maru*	Do.
29	June 4, 1958	NRFRL	do	June 24, 1958	do	unknown	Do.
30	May 26, 1958	NRFRL	do	June 28, 1958	do	do	Do.
31	June 4, 1958	NRFRL	do	July 4, 1958	do	do	Do.
32	May 26, 1958	NRFRL	do	Jan. 13, 1960	do	do	Longline.
33	July 7, 1959	OFC	Trolling	July 13, 1960	do	*Taiwa Maru*	Livebait.
34	Sept. 10, 1960	OFC	Seine	Sept. 10, 1960	American	unknown	Do.
35	Sept. 10, 1960	OFC	do	Sept. 13, 1960	do	do	Do.

Recovery No.	Release			Recapture			
	Position		Size (cm.)	Position		Size (cm.)	Days out
	Latitude	Longitude		Latitude	Longitude		
18	33°25′ N	118°15′ W	76.0	31°30′ N	149°40′ E		32
19	29°00′ N	118°30′ W	84.0	36°40′ N	178°12′ E	88.0	17
20	29°00′ N	118°30′ W	91.0	30°10′ N	178°54′ W	93.0	19
21	33°42′ N	121°15′ W		31°55′ N	143°15′ E	ca. 75	19
22	36°39′ N	123°16′ W		35°50′ N	142°50′ E		27
23	39°57′ N	130°38′ W		34°30′ N	142°00′ E	75.7	29
24	33°00′ N	143°45′ E	ca. 81	32°01′ N	144°58′ E		2
25	33°18′ N	143°31′ E	ca. 81	33°40′ N	144°40′ E	79.1	1
26	32°59′ N	143°19′ E	ca. 81	32°07′ N	144°52′ E		1
27	33°00′ N	143°45′ E	ca. 87	35°23′ N	148°54′ E	84.8	2
28	33°00′ N	143°45′ E	ca. 82	33°58′ N	152°20′ E	81.5	3
29	33°18′ N	143°31′ E	ca. 85	34°18′ N	152°51′ E		2
30	33°00′ N	143°45′ E		34°37′ N	153°03′ E	76.5	3
31	33°18′ N	143°31′ E	ca. 83	33°52′ N	154°21′ E		3
32	33°00′ N	143°45′ E	ca. 70	33°08′ N	138°15′ E	ca. 92	59
33	43°01′ N	125°34′ W	67.0	33°53′ N	152°23′ E		37
34	46°01′ N	126°30′ W	66.0	46°04′ N	126°27′ W		4 hr
35	46°04′ N	126°27′ W	68.0	46°10′ N	126°10′ W		

[1] CFG=California Department of Fish and Game; OFC=Fish Commission of Oregon; and NRFRL=Nankai Regional Fisheries Research Laboratory

[2] Data of the California tag recoveries were reported by Ganssle and Clemens (1953), Blunt (1954), Investigative Society of Tuna Fishery (1955), and in personal correspondence from H. B. Clemens dated July 9, 1957.

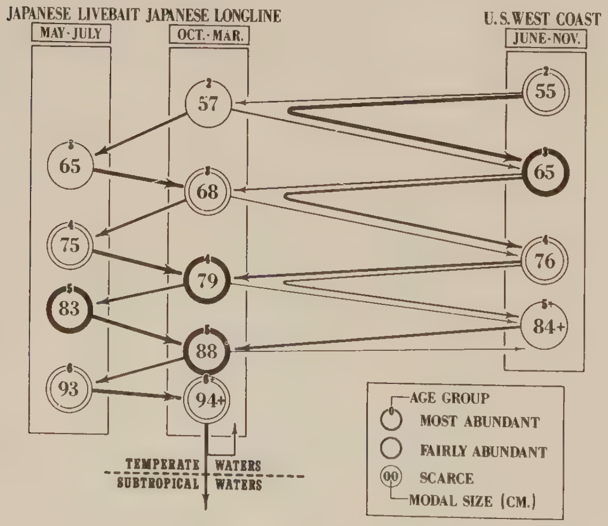

Figure 8.—Diagrammatic representation of albacore migration, by size (age) groups.

Figure 8 is a diagrammatic representation of the movements of albacore among the three fisheries. Since the sizes of the fish differ from one fishery to another (fig. 5), the migration of the albacore is hypothesized on the basis of size (age) groups. The approximate modal size for each year class in the catch is shown for each fishery. While it is not possible to describe quantitatively the movements among the fisheries, the following types or patterns of movements are the major elements in our suggested model of North Pacific albacore migrations:

I–a. This is the westward migration, in the fall, of 2-year-old (55 cm.) fish from the area of the American fishery. These albacore have been only partly recruited into the exploited stock at age 2; their recruitment will be completed when they are 3 years old. The majority of 2-year-olds do not t far enough west to reach the center of the panese winter longline fishery, and they may not en reach the eastern fringe of the developing nter longline grounds. In either case they do t migrate with the main body of southwesterly grating fish in the longline fishery, but remain tside the area of any fishery until they return the American fishery the following season as ear-olds.

I–b. The remaining 2-year-olds, those that do ach the center of the Japanese longline fishery, ntinue moving in a southwesterly direction tween October and March and enter the Japan- e livebait fishery in the spring as 3-year-olds. is group is apparently small, judging by the all numbers of 3-year-olds in the Japanese live- it catch.

II–a. The 3-year-olds (65 cm.), which are the jor components of the American catch, may gin their westerly migration as early as August September, but a significant portion of this oup departs later in the season and does not ach the center of the Japanese longline fishery. ese fish return to the American fishery the fol- ving summer as 4-year-olds.

II–b. The rest of the 3-year-olds, perhaps an ually significant portion, judging from the num- rs of this year class in the American fishery d the Japanese longline fishery (fig. 5), enter e Japanese longline fishery by early winter. ese fish continue westward to enter the Japa- se livebait fishery the following spring as 4-year- ls.

III–a. The bulk of the third age group in the erican catch, the 4-year-olds (76 cm.), migrate stward from the American fishery into the panese longline fishery and subsequently con- ue into the Japanese livebait fishery as 5-year- ls.

III–b. A small fraction of the 4-year-olds sep- tes from the others and returns to the American ery the following summer as 5-year-olds. is is only a small fraction, however, since 5- ar-olds are an insignificant proportion of the erican catch.

IV–a. Nearly all of the 5-year-old and older in the American fishery migrate into the panese livebait fishery by way of the Japanese gline fishery.

IV–b. A few of these older fish do separate and urn to the American fishery. This is indicated by a tag recovery (table 1 and fig. 10, Recovery No. 14).

V–a. The Japanese livebait fishery is notably lacking in 2- and 3-year-old fish, which are fairly abundant in the American fishery. Such small fish, when present, may migrate into the American fishery after spending a part of the season in the longline fishery.

V–b. Of the more common sizes of fish in the Japanese livebait fishery, only the two youngest groups (the 4- and 5-year-olds) provide some fish which migrate into the American fishery. However, these are few, since by the time they enter the American fishery they are already 5- and 6-year-olds, and these age groups make an insignificant contribution to the American catch.

VI. The Japanese winter longline fishery receives fish from both the Japanese livebait fishery and the American fishery. From the longline fishery, the greater part of the albacore move into the Japanese livebait fishery, while the rest migrate east into the American fishery.

VII. The 6-year-olds (94 cm.) and older age groups in the winter longline fishery do not enter into either of the other two fisheries. A portion of these fish, having attained sexual maturity in temperate waters (albacore mature at around 90 cm.), move south into subtropical waters in the spring to form the reproductive unit of the North Pacific population (Ueyanagi, 1957; Otsu and Uchida, 1959). Since these older fish are always present in the winter longline fishery, it is apparent that at least some of them return north in the spring, possibly to the east of and beyond reach of the Japanese livebait fishery.

VIII. Most of the groups of fish exploited in the Japanese livebait fishery move from that fishery into the winter longline fishery and then back into the livebait fishery, thus remaining in the western North Pacific. Judging by the sizes of fish exploited, it is clear that only a small fraction of the fish in the livebait fishery migrate across the Pacific into the American fishery.

The above model is summarized in table 3, and the general pattern of migration of albacore in the North Pacific is illustrated in figure 9.

DISCUSSION

Data from tag recoveries support the model and thus the underlying hypothesis that there is a single population of albacore in the North Pacific

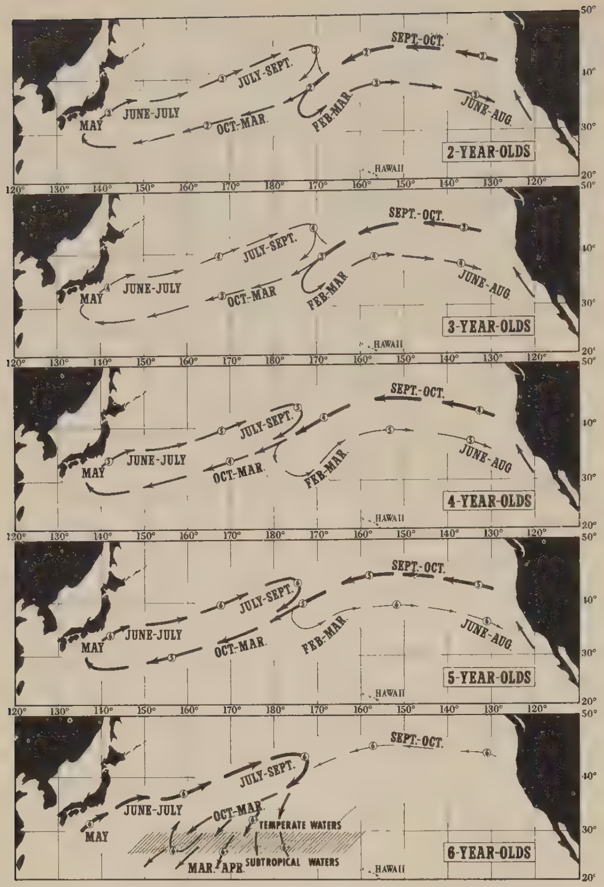

Figure 9.—Model of albacore migrations in the North Pacific Ocean, by age groups (ages encircled).

Ocean. In figure 10 and table 4 are shown the postulated migrations of each of the tagged fish recovered to date. The migration believed undertaken by each fish between tagging and recovery is related to one or more of the types of movement described in the preceding section and summarized in table 3.

There has not been any recovery of fish tagged as 2-year-olds in the American fishery, but this is understandable in view of their small number. Of 218 fish tagged by the Bureau of Commercial Fisheries Biological Laboratory, Honolulu, in the general area of this fishery between longitudes 110° W. and 127° W., only 11 were 2-year-old fish. Judging from the fact that this age group is poorly represented in the Japanese longline fishery and that 3-year-olds are very scarce in the Japanese livebait fishery, it can be assumed that most of the fish return to the American fishery the following season and, along with new recruits, form the dominant 3-year-old age group (type I-a). The others probably constitute the 2-year-olds in the longline catch and the 3-year-olds in the following year's Japanese livebait catch (type I-b).

It has been hypothesized that a portion of the large adults occurring in the Japanese winter longline fishery move south during the spring into subtropical waters to form the reproductive part of the North Pacific population (Ueyanagi, 1957; Otsu and Uchida, 1959). We believe that it is fish from this group that appear in the Hawaiian longline fishery each year and contribute to an increase in landings beginning around April. However, since the annual landings of albacore in Hawaii are very small (between 10,000 and 21,000 pounds during the 1955–59 period), it is possible that the Hawaiian Islands are on the eastern fringe of this southward migration.

Otsu and Uchida (1959) have suggested that the albacore occurring in Hawaiian waters are a segment of the North Pacific spawning population. They also agree with Ueyanagi (1957) that albacore spawning probably takes place in subtropical waters in the areas under the influence of the

Table 3.—*Summary of the model of albacore migrations in the North Pacific Ocean*

Type of movement	Pattern of movement among fisheries
I-a	(most) U.S. west coast⟶midocean [1]⟶U.S. west coast (2-year-olds) (3-year-olds)
I-b	U.S. west coast⟶Japanese longline→Japanese livebait (2-year-olds) (3-year-olds)
II-a	U.S. west coast⟶midocean⟶U.S. west coast (3-year-olds) (4-year-olds)
II-b	U.S. west coast⟶Japanese longline→Japanese livebait (3-year-olds) (4-year-olds)
III-a	(most) U.S. west coast⟶Japanese longline→Japanese livebait (4-year-olds) (5-year-olds)
III-b	(few) U.S. west coast⟶midocean⟶U.S. west coast (4-year-olds) (5-year-olds)
IV-a	(most) U.S. west coast⟶Japanese longline⟶Japanese livebait (5-year-olds and older) (6-year-olds and older)
IV-b	(few) U.S. west coast⟶midocean⟶U.S. west coast (5-year-olds and older) (6-year-olds and older)
V-a	(few) Japanese livebait→Japanese longline→U.S. west coast (2-, 3-year-olds) (3-, 4-year-olds)
V-b	(few) Japanese livebait→Japanese longline→U.S. west coast (4-, 5-year-olds) (5-, 6-year-olds)
VI	U.S. west coast⟶Japanese longline←Japanese livebait (2-, 3-, 4-, 5+-year-olds) (Mixing) (3-, 4-, 5-, 6-year-olds)
VII	Japanese longline→Subtropical Convergence→Subtropical waters, spawning (6-year-olds and older)
VIII	U.S. west coast⟵⟶Japanese longline ←→Japanese livebait (few) (most)

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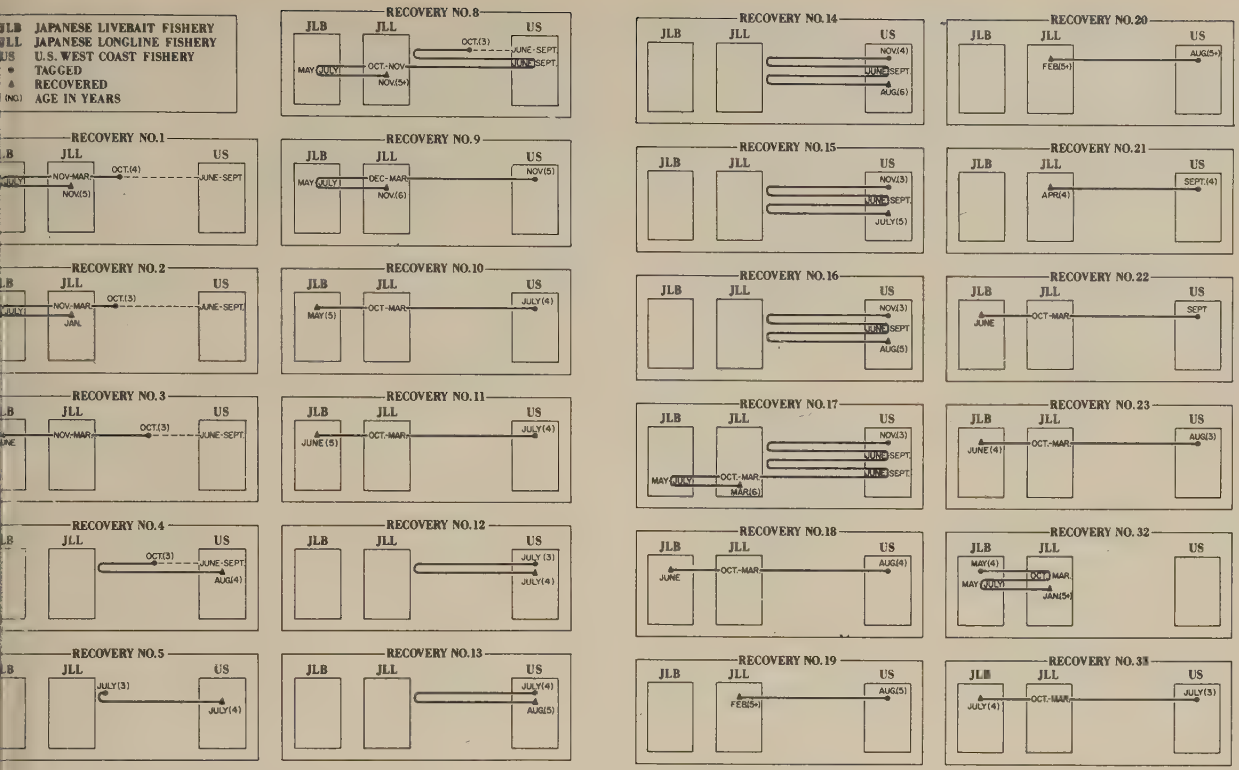
[1] This term refers to the general area between the center of the Japanese longline fishery and the U.S. west coast, and including the eastern fringe of the longline fishery.


LB JAPANESE LIVEBAIT FISHERY
LL JAPANESE LONGLINE FISHERY
JS U.S. WEST COAST FISHERY
TAGGED
RECOVERED
(NO.) AGE IN YEARS
RECOVERY NO.1
RECOVERY NO.2
RECOVERY NO.3
RECOVERY NO.4
RECOVERY NO.5
RECOVERY NO.8
RECOVERY NO.9
RECOVERY NO.10
RECOVERY NO.11
RECOVERY NO.12
RECOVERY NO.13
RECOVERY NO.14
RECOVERY NO.15
RECOVERY NO.16
RECOVERY NO.17
RECOVERY NO.18
RECOVERY NO.19
RECOVERY NO.20
RECOVERY NO.21
RECOVERY NO.22
RECOVERY NO.23
RECOVERY NO.32
RECOVERY NO.33
JLB
JLL
US
MAY
JULY
JUNE
JUNE-SEPT.
OCT.-NOV.
NOV.-MAR.
DEC.-MAR.
OCT.-MAR.
SEPT.
SEPT
OCT.(3)
OCT.(4)
NOV.(4)
NOV.(5)
NOV.(5+)
NOV.(6)
NOV.(3)
JAN.
MAY(5)
MAY(4)
JUNE(5)
JUNE(4)
JULY(3)
JULY(4)
JULY(5)
AUG.(4)
AUG.(5)
AUG.(5+)
AUG.(6)
AUG.(3)
FEB.(5+)
APR.(4)
SEPT.(4)
MAR.(6)
OCT.
MAR.
JAN.(5+)

IGURE 10.—Diagrammatic representation of the postulated migrations of albacore between tagging and recovery (see table 4).

rth Equatorial Current. It seems a reasonable oothesis that spawning occurs during the sum- in subtropical waters (the exact spawning unds have not yet been defined), and that the val and early juvenile stages are spent in these ers. The collection of young albacore from mach contents of predator species (Yabe et al., 8) indicates the occurrence of these stages subtropical waters. At a later stage, perhaps en the fish are about a year old, they migrate temperate waters but do not immediately the exploited stock (Suda, 1958).

s stated previously the Japanese livebait fish- occasionally encounters 1-year-old fish (about cm.). There have been similar occurrences of all fish in the American fishery, for example, ing the summer of 1954, when the fishery was ortedly characterized by the appearance of all fish (personal communications, Inter- erican Tropical Tuna Commission). Such al fish are probably abundant generally ughout temperate waters, but are not avail- to the commercial fisheries until they reach age of 2 or 3.

The virtual absence of 2-year-olds in the Japanese livebait catch, and the relatively small number of this age group in the longline fishery, seem to indicate that recruitment into the exploited stock occurs primarily in the American fishery. This apparent concentration of recruitment in the eastern Pacific may be exaggerated by gear selectivity, as the longline gear used in the central Pacific would not be expected to sample such small fish effectively for several reasons. This objection would not hold, however, in the Japanese livebait fishery, and so it is apparent that the major portion of the recruitment is taking place in the eastern rather than the western North Pacific.

In general, our model indicates a greater volume of migration of the commerical sizes of albacore in the westerly direction, from the American fishery into the Japanese fisheries, than vice versa. At the same time, it indicates that a significant portion of the fish entering the American fishery does not migrate directly into the Japanese fisheries, but instead is exploited over 3 or 4 seasons in the American fishery. Furthermore, the sizes

Table 4.—*Postulated migration of albacore between tagging and recovery*

[Each recovery is related to a "type of movement," shown in table 3.]

Recovery No.	Type of movement	Postulated migration [1]
1	III-a, VIII	US (June-Sept.) → MO (tagged) (Oct.) (78.2 cm.) → JLL (Nov.-Mar.) → JLB (May-July) → JLL (recovered) (Nov.) (size unknown)
2	II-b, VIII	US (June-Sept.) → MO (tagged) (Oct.) (68 cm.) → JLL (Nov.)-Mar.) → JLB (May-July) → JLL (recovered) (Jan.) (size unknown)
3	II-b	US (June-Sept.) → MO (tagged) (Oct.) (63.4 cm.) → JLL (Nov.-Mar.) → JLB (recovered) (June) (size unknown)
4	II-a	US (June-Sept.) → MO (tagged) (Oct.) (59.9 cm.) → US (recovered) (Aug.) (72.3 cm.)
5	II-a	MO (tagged) (July) (68.4 cm.) → MO (Oct.-Mar.) → US (recovered) (July) (78.0 cm.)
6		Tagged and recovered in American fishery during same season.
7		
8	II-a, III-a, VIII	US (June-Sept.) → MO (tagged) (Oct.) (65.1 cm.) → US (June-Sept.) → JLL (Oct.-Mar.) → JLB (May-July) → JLL (recovered) (Nov.) (94.8 cm.)
9	IV-a, VIII	US (tagged) (Nov.) (85.2 cm.) → JLL (Dec.-Mar.) → JLB (May-July) → JLL (recovered) (Nov.) (97.5 cm.)
10	II-a	US (tagged) (July) (78 cm.) → JLL (Oct.-Mar.) → JLB (recovered) (May) (85.2 cm.)
11	III-a	US (tagged) (July) (75 cm.) → JLL (Oct.-Mar.) → JLB (recovered) (June) (size unknown)
12	II-a	US (tagged) (July) (65 cm.) → MO (Oct.-Mar.) → US (recovered) (July) (77.3 cm.)
13	III-b	US (tagged) (July) (75 cm.) → MO (Oct.-Mar.) → US (recovered) (Aug.) (84.5 cm.)
14	II-b, IV-b	US (tagged) (Nov.) (79.4 cm.) → MO (Dec.-Mar.) → US (June-Sept.) → MO (Oct.-Mar.) → US (recovered) (Aug.) (92.6 cm.)
15	II-a, III-b	US (tagged) (Nov.) (68.6 cm.) → MO (Dec.-Mar.) → US (June-Sept.) → MO (Oct.-Mar.) → US (recovered) (July) (86.4 cm.)
16	II-a, III-b	US (tagged) (Nov.) (65.9 cm.) → MO (Dec.-Mar.) → US (June-Sept.) → MO (Oct.-Mar.) → US (recovered) (Aug.) (81.2 cm.)
17	II-a, III-b, IV-a, VIII	US (tagged) (Nov.) (60.8 cm.) → MO (Dec.-Mar.) → US (June-Sept.) → MO (Oct.-Mar.) → US (June-Sept.) → JLL (Oct.-Mar.) → JLB (May-July) → JLL (recovered) (Mar.) (90 cm.)
18	III-a	US (tagged) (Aug.) (76.0 cm.) → JLL (Oct.-Mar.) → JLB (recovered) (June) (size unknown)
19	IV-a	US (tagged) (Aug.) (84 cm.) → JLL (recovered) (Feb.) (88 cm.)
20	IV-a	US (tagged) (Aug.) (91 cm.) → JLL (recovered) (Feb.) (93 cm.)
21	III-a	US (tagged) (Sept.) (size unknown) → JLL (recovered) (Apr.) (ca. 75 cm.)
22		US (tagged) (Sept.) (size unknown) → JLL (Oct.-Mar.) → JLB (recovered) (June) (size unknown)
23	II-b	US (tagged) (Aug.) (size unknown) → JLL (Oct.-Mar.) → JLB (recovered) (June) (75.7 cm.)
24-31		Tagged and recovered in livebait fishery during same season.
32	VIII	JLB (tagged) (May) (ca. 70 cm.) → JLL (Oct.-Mar.) → JLB (May-July) → JLL (recovered) (Jan.) (ca. 92 cm.)
33	II-b	US (tagged) (July) (67 cm.) → JLL (Oct.-Mar.) → JLB (recovered) (July) (size unknown)
34-35		Tagged and recovered in American fishery during same season.

[1] US=American fishery; JLL=Japanese longline fishery; JLB=Japanese livebait fishery; MO=midocean between Japanese longline fishery and U.S. west coast, or on eastern fringe of Japanese longline fishery.

of fish commonly exploited by the Japanese livebait fishery (4-, 5-, and 6-year-olds) are such that only a small percentage would appear later in the American fishery. This is, to a large extent, also true of the Japanese longline fishery, which takes largely the 4-, 5-, and 6-year-old fish.

It is therefore easy to understand why tagging in the Japanese livebait fishery has not resulted in any recoveries in the American fishery. The chances of such recoveries are slim because of the small number of fish of these older age groups appearing in the American catch. Tagging of the less common smaller fish in the livebait or longline fisheries should increase the chances of recoveries in the American fishery.

SUMMARY

1. A model of the migration of albacore in the North Pacific Ocean is proposed on the basis of tag recovery data, age and growth information, and distribution and size frequency data from various fisheries. This model is consistent with the hypothesis that there is a single population of albacore in the North Pacific Ocean.

2. The migration of albacore within the areas of the three major fisheries is in general reflected by the seasonal shifting of the respective fishing grounds. The Japanese livebait fishery begins off southern Japan in late April or May and gradually moves in the north and northeasterly directions. In July the fishery rapidly declines

the fish move offshore from central Japan in
easterly direction.

The Japanese longline fishery begins in October
th its center of abundance located in midocean
tween longitudes 170° E. and 180°, and along
itude 38° N. The fishery generally shifts in a
thwesterly direction with the advance of the
son. At the end of the season, in March, the
ter of concentration is located around 30° N.,
° E.

The American fishery begins off Baja California
June and gradually shifts north along the coast,
well as offshore, as the season progresses.

3. Tag recoveries have shown transpacific
vements of albacore from the American fishery
o the Japanese longline and livebait fisheries
d from midocean into both the American and
panese fisheries. Tagging in the Japanese
ebait fishery has produced one recapture in the
gline fishery.

4. The three North Pacific fisheries exploit
ferent sizes of fish. Assuming that the first
ar's growth of albacore is about 30 cm., it is
stulated that the fish are 2-years-old (about
cm.) when they first enter the commercial
eries. On this basis it is shown that the
panese livebait fishery takes four groups, which
approximately 3-, 4-, 5-, and 6-year-old fish,
h modal lengths of 65, 75, 83, and 93 cm.
e-year-old fish are usually the principal com-
nent of the catch. The catches in the winter
gline fishery are composed of 2- to 8- or 9-
r-old fish, with modal lengths of approximately
68, 79, 88, 94 cm., and larger. The 4- and
ear-old fish are most numerous in the catch.
e American fishery usually exploits 2-, 3-, and
ear-old fish (55, 65, 76 cm.), but small numbers
older age groups (5- and 6-year-olds) also
pear in the catches. The 3-year-old fish are
erally most abundant. These differences in
es among the fisheries are considered in devel-
ng the model of albacore migration.

5. It is postulated that albacore undertake no
re than one transpacific migration within a
ear period.

6. The model of the migration of albacore
ong the fisheries is briefly as follows: a varying
tion of the 2-, 3-, and 4-year-old fish and
rly all of the older fish in the American fishery
grate westward into the Japanese longline
ery, and subsequently into the Japanese livebait fishery the following spring. The remainder either do not reach, or may possibly enter the fringe of the Japanese longline fishery, and return to the American fishery the following summer. Consequently, some of the fish may be available to the American fishery for as many as four or five seasons (fig. 8).

The Japanese livebait fishery is notably lacking in 2- and 3-year-old fish. Such small fish, when present, may migrate into the American fishery after spending a part of the season in the winter longline fishery. Of the more common sizes in the livebait fishery, only the 4- and 5-year-old groups provide some fish that enter the American fishery the following summer, but these are few since 5- and 6-year-old fish comprise only a very small proportion in the American catch. The bulk of the fish from the livebait fishery migrate into the longline fishery in the fall and return to the livebait fishery the following spring.

Fish enter the winter longline fishery from both the American fishery and the Japanese livebait fishery. A large part of these fish migrate southwestward in the winter longline fishery, and subsequently enter the livebait fishery in the spring, while a few separate and migrate into the American fishery by summer.

A portion of the large adults occurring in the Japanese winter longline fishery (6-year-olds and older) move south during the spring into subtropical waters, where they make up the reproductive unit of the North Pacific population.

7. It is hypothesized that spawning occurs in subtropical waters during the summer, and that the larval and early juvenile stages are spent in these waters. When about a year old, the fish migrate into temperate waters, but they do not immediately join the exploited stock. The albacore are generally not available to commercial fisheries until they reach the age of 2 or 3.

8. It appears that most of the recruitment into the exploited stock takes place in the eastern rather than the western North Pacific. There is a greater volume of migration of the commercial sizes of albacore in the westerly direction from the American fishery into the Japanese fisheries, than vice versa.

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RTHER STUDIES ON FISHWAY SLOPE AND ITS EFFECT ON RATE OF PASSAGE OF SALMONIDS

By JOSEPH R. GAULEY AND CLARK S. THOMPSON, *Fishery Biologists*

BUREAU OF COMMERCIAL FISHERIES

ABSTRACT

he rates of passage of chinook (*Oncorhynchus* wytscha) and sockeye (*O. nerka*) salmon and steel- l trout (*Salmo gairdneri*) were studied in 1:16- and slope, pool-and-overfall fishways. In general, the age of salmonids through the 1:8-slope fishway a 1.0-foot rise between pools was as fast as, or er than, in the 1:16-slope fishway with a 1.0-foot rise. When the rise between pools was increased to 1.5 feet in the 1:8-slope fishway, chinook and sockeye were slower. The "Dalles-type" weir crests in a 1:16-slope fishway appeared to accelerate chinook passage. Chinook and sockeye displayed seasonal differences in times within the species.

he effect of fishway slope[1] on the passage of is an important factor in fishway design. equal importance is the potential saving in truction costs which will accrue if it can be onstrated that fishways with steeper slopes fish equally as well as the presently accepted dard designs.

ears of water resource development on the Col- ia River for irrigation, power, and flood con- have produced a multitude of problems ing to the passage of anadromous fishes.

sh passage requirements and criteria con- te a continuing problem in fishway con- ction. Varying physical and biological itions require constant research to meet demands in each specific instance. Intensive ts to provide an economical solution to our passage problems at dams bring into focus need for basic information on the reaction of ream migrant salmon to various physical characteristics of fishways. Until recently little research has been done on fish passage requirements.

Slopes of 1:20, 1:16, and 1:10 are found in existing fishways on the Columbia River. The 1:16 slope has come to be the accepted standard for the larger fishways. If a steeper slope shows equal fish-passing ability, fishway construction costs can be reduced. Scientists at the fisheries-engineering research project, located at Bonneville Dam on the Columbia River, are studying the reaction of migrating salmon to different fishway slopes and other factors that may influence the passage of salmon at dams.[2]

This paper presents a continuation of research, reported by Gauley (1960) on the effect of fishway slope and other factors on the rate of passage of salmonids. The results of this research provide basic information for the solution of fishway problems.

EXPERIMENTAL EQUIPMENT

LABORATORY

The research facilities are adjacent to the Washington shore fishways (figs. 1 and 2). Collins and Elling (1960) present a detailed descrip-

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E.--Approved for publication February 5, 1962.

hway slope is defined as the ratio of the rise or vertical distance to the horizontal distance.

s project was financed by the U.S. Army Corps of Engineers as part oad program of fisheries-engineering research for the purpose of pro- design criteria for more economical and more efficient fish-passage s at Corps projects on the Columbia River.

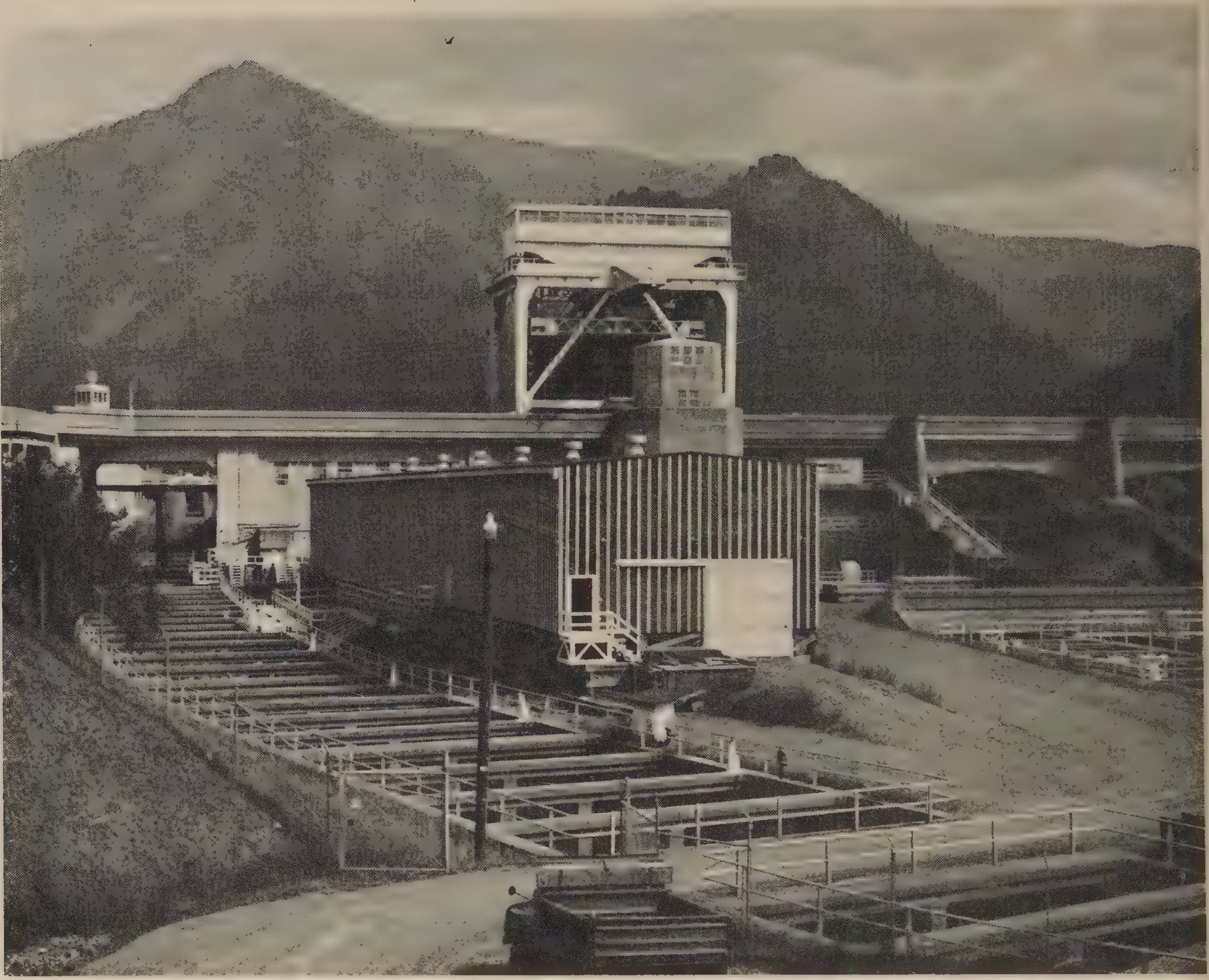


Figure 1—Research facilities at Bonneville Dam. The north end of the main dam is shown in the background and part of the Washington shore fishway in the foreground.

tion of the laboratory. In brief, the key features for operation of the facility are (1) the procurement of fish and (2) the introduction and control of water.

A removable picketed lead blocks a small portion of the Washington shore fishway, thus diverting fish into a short entrance fishway leading to a collecting pool in the laboratory. Test fish leave the laboratory through a short exit fishway which returns them to the main fishway.

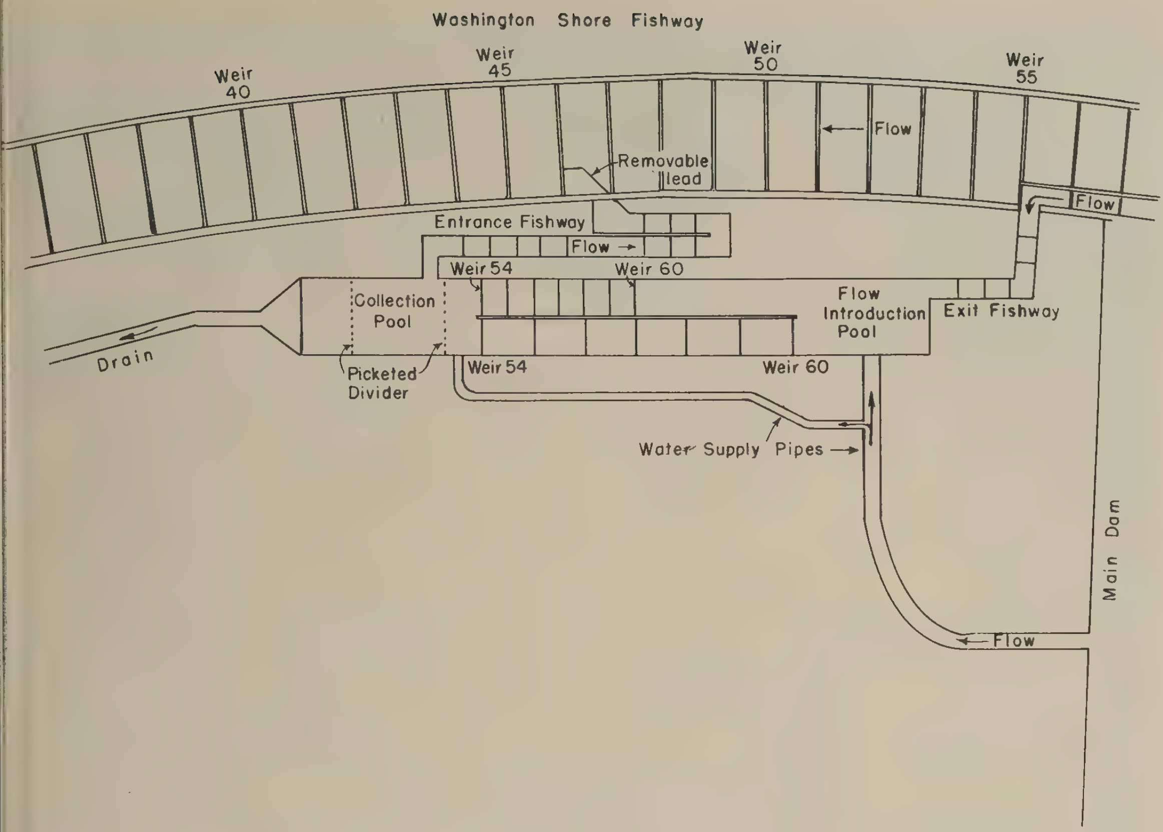
The water is supplied by two sources and controlled by a system of pipes and valves. Most of the water is supplied from the forebay through a large conduit to the flow introduction pool in the laboratory. The maximum flow is about 200 cubic feet per second (c.f.s.). Water from the main fishway (about 20 c.f.s.) supplies the exit fishway. A series of valves control the inflow of water, and drain valves control the outflow so that hydraulic conditions in the test and control fishway can be accurately controlled.

FISHWAYS

Fish passage was studied in two pool-and-overfall fishways without submerged orifices. The total gain in elevation was the same for both fish-ways, although physical characteristics of each could be altered independently.

Slopes

The experimental fishways were constructed of prefabricated frames and heavy plywood panels. By erecting a center wall, the test area was divided into two passageways 11.5 feet wide. The slopes in both passageways could be made identical, or


Washington Shore Fishway
Weir 40
Weir 45
Weir 50
Weir 55
Flow
Removable lead
Flow
Entrance Fishway
Flow
Weir 54
Weir 60
Collection Pool
Flow Introduction Pool
Exit Fishway
Drain
Picketed Divider
Weir 54
Weir 60
Water Supply Pipes
Main Dam
Flow

GURE 2—General plan of the laboratory, bypass, and associated experimental components. Weir designations indicate elevation in feet above mean sea level.

could be altered independently without dis- ng the other by installing the fishway floors in iously constructed sections to give the desired (figs. 3 and 4).

e fishway weirs which were transferable were tructed with concrete bases to reduce buoyancy. he addition or removal of weirs, rise between could be changed. Such changes were made in the test fishway.

e course of studies utilized two fishway s—1:16 (control) and 1:8 (test). The con- fishway remained unchanged throughout the season except during a brief period of altered fishway width and weir crests. During the season 1.0-foot and 1.5-foot rises between pools were tested in the 1:8-slope fishway.

E 1.—*Dimensions of fishways used in the slope studies during 1957*

hway ype	Slope	Number of pools	Pool length	Pool width	Mean pool depth	Rise between pools	Elevation gained
			Feet	*Feet*	*Feet*	*Feet*	*Feet*
	1:16	6	16.0	11.5	6.30	1.0	6
	1:16	6	16.0	4.0	6.30	1.0	6
	1:8	6	8.0	11.5	6.30	1.0	6
	1:8	4	12.0	11.5	6.05	1.5	6

Dalles-type weir crest (fig. 12) used in this fishway.

Table 1 and figure 5 give the dimensions of fishways used during the 1957 experiments. Hereafter, in the interest of brevity, fishway type numbers will be used to identify the various fishway dimensions and slopes.

Lighting

Controlled light conditions were provided by a battery of 1,000-watt mercury-vapor lamps (fig. 6) which could be adjusted vertically above the water surface, so that identical light intensities prevailed in both fishways. The lamps were suspended vertically 6 feet above the water surface where they produced an average incident light intensity of 700 foot-candles. The range was 300 to 1,000 foot-candles. Light measurements directly beneath the reflectors were highest, whereas the

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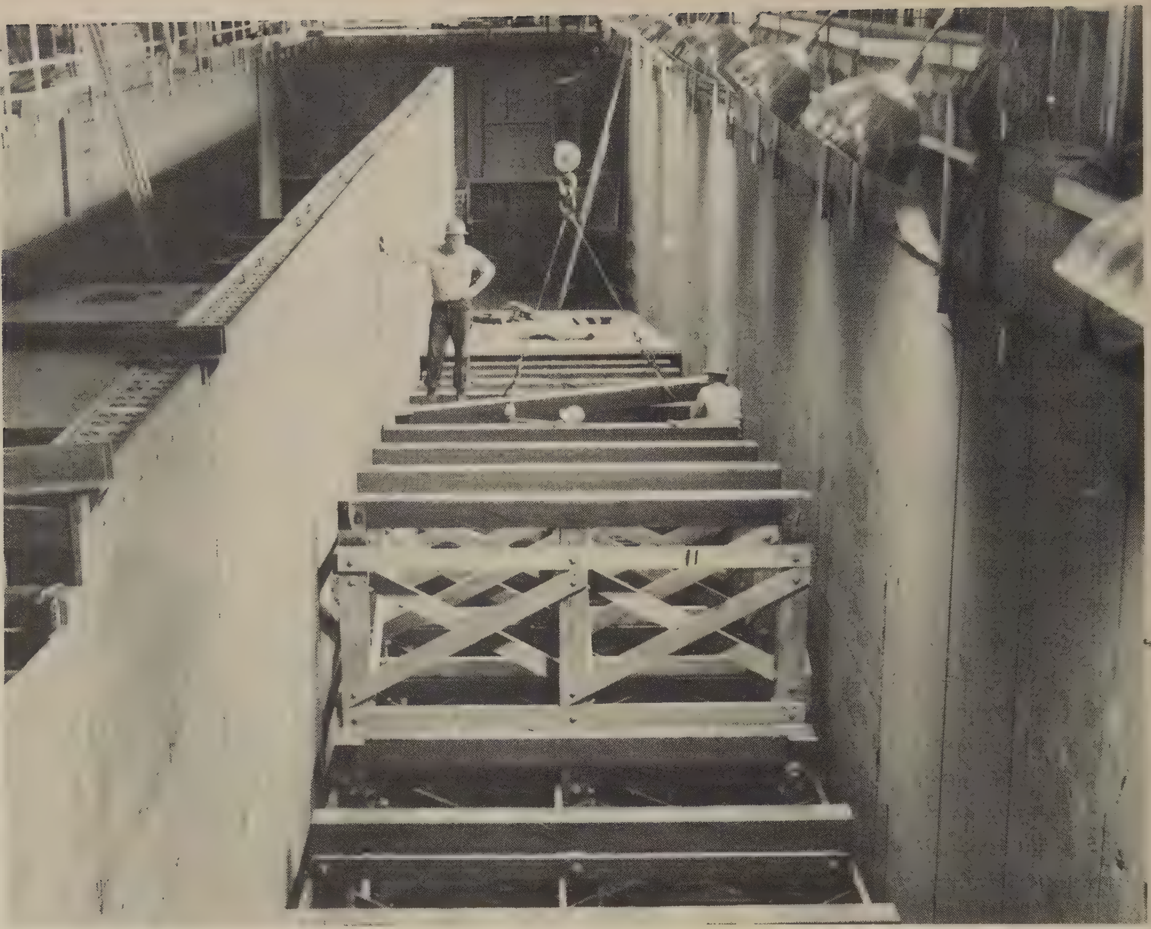


Figure 3—Installation of floor frames for the 1:8-slope fishway. A section of floor is in place at the lower end of the fishway.

lower readings were recorded along the walls. These light conditions were comparable to lighting in the main Bonneville fishway during a bright cloudy day.

Hydraulic Conditions

Waterflow through the test area was maintained by regulating the flow of water into the flow introduction pool. Keeping a constant head on the uppermost weir crest permitted maintenance of the water flowing over the fishway weirs at a head of 0.8 foot measured 4 feet upstream from the weir crest. This was the maximum depth at which the desired plunging flow over the weir crests could be stabilized. More water caused a streaming flow in the fishways, which had been demonstrated to temporarily interrupt fish passage (Elling and Raymond, 1959).

METHODS

Release and timing of fish

To evaluate properly the effects of fishwa slope on salmonids, the performance of eac species both as an individual and in groups, a well as the composite performance of all specie must be considered. With this in mind w employed the following three types of release (1) an individual fish ascending the fishway alon (2) groups in which 21 fish of the same specie were timed as a group, and (3) mass release representing all species available.

Individuals

Fish were released into both fishways throug the picketed divider at the upstream end of th collection pool. Figure 7 is a side view lookin down on the release compartment. The collectio

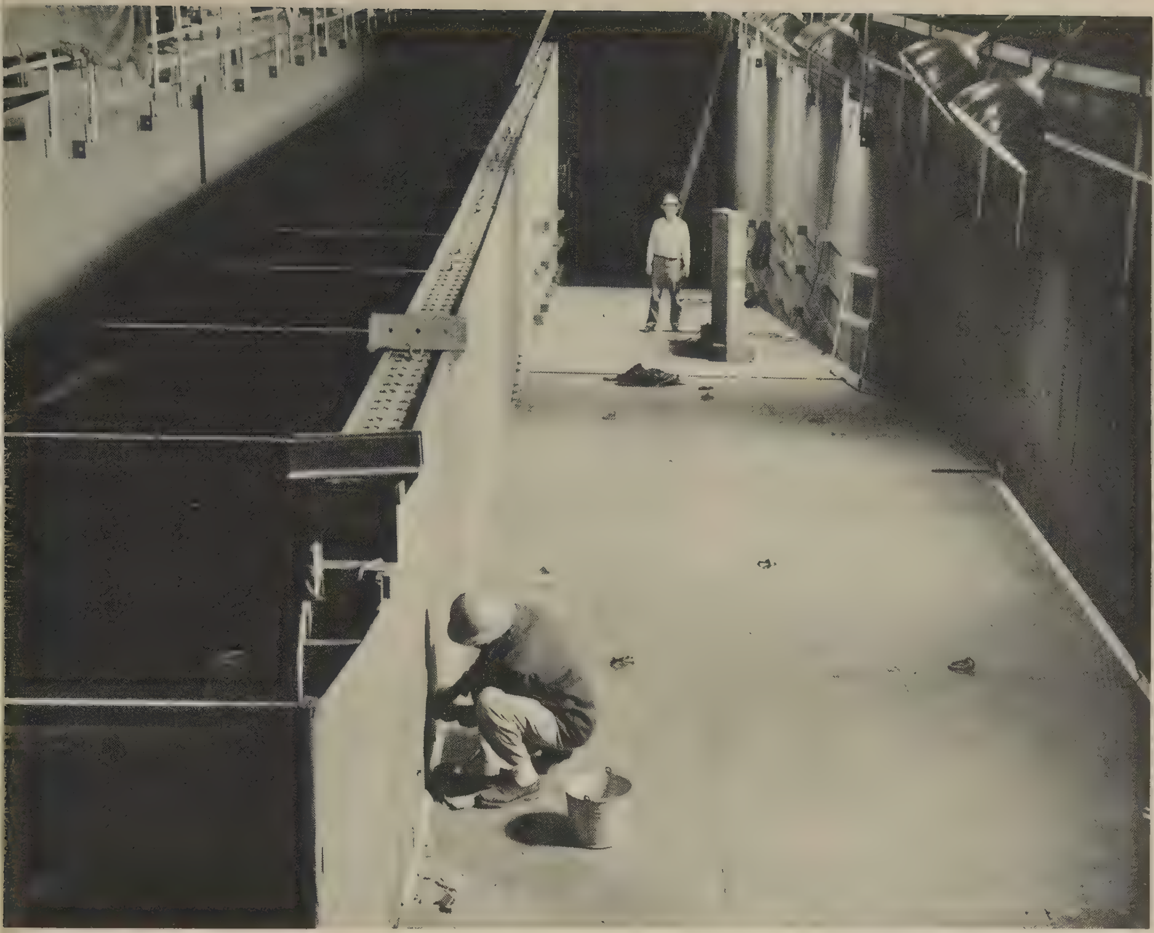
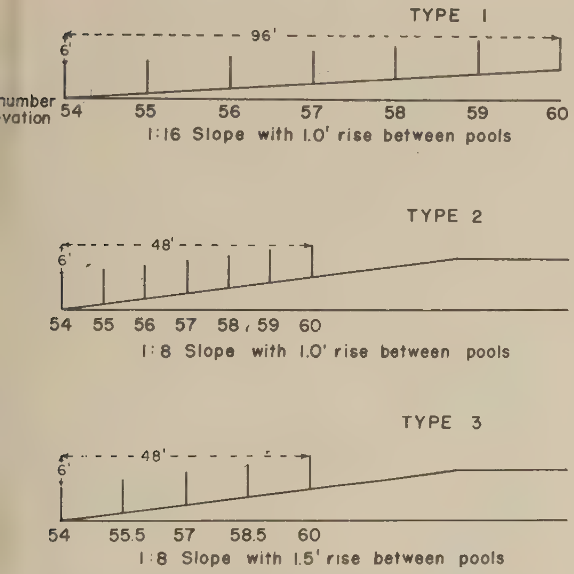


Figure 4—The 1:8-slope fishway floor. Wall brackets mark the locations for weirs.


TYPE 1
96'
6'
number
vation
54
55
56
57
58
59
60
1:16 Slope with 1.0' rise between pools
TYPE 2
48'
6'
54
55
56
57
58
59
60
1:8 Slope with 1.0' rise between pools
TYPE 3
48'
6'
54
55.5
57
58.5
60
1:8 Slope with 1.5' rise between pools

RE 5.—Diagrammatic drawing showing weir placement for the two fishway slopes.

pool is visible at the left margin behind the divider.

The operator at the left has raised the entrance gate to the release compartment to admit a fish from the collection pool, while the operator on the right is preparing to raise the exit gate to the introductory area leading to the test fishway. The second exit gate leads to the control fishway. As each fishway was vacated, another fish was released into the vacant fishway.

During the brief passage through the release compartment each fish was identified by species, and its length was estimated.

The time spent in each pool (pool time) and the total time required to ascend the fishway were kept on separate stop watches. Pool times were obtained by an observer starting one watch and stopping a second one simultaneously as the fish crossed each weir. A second observer timed

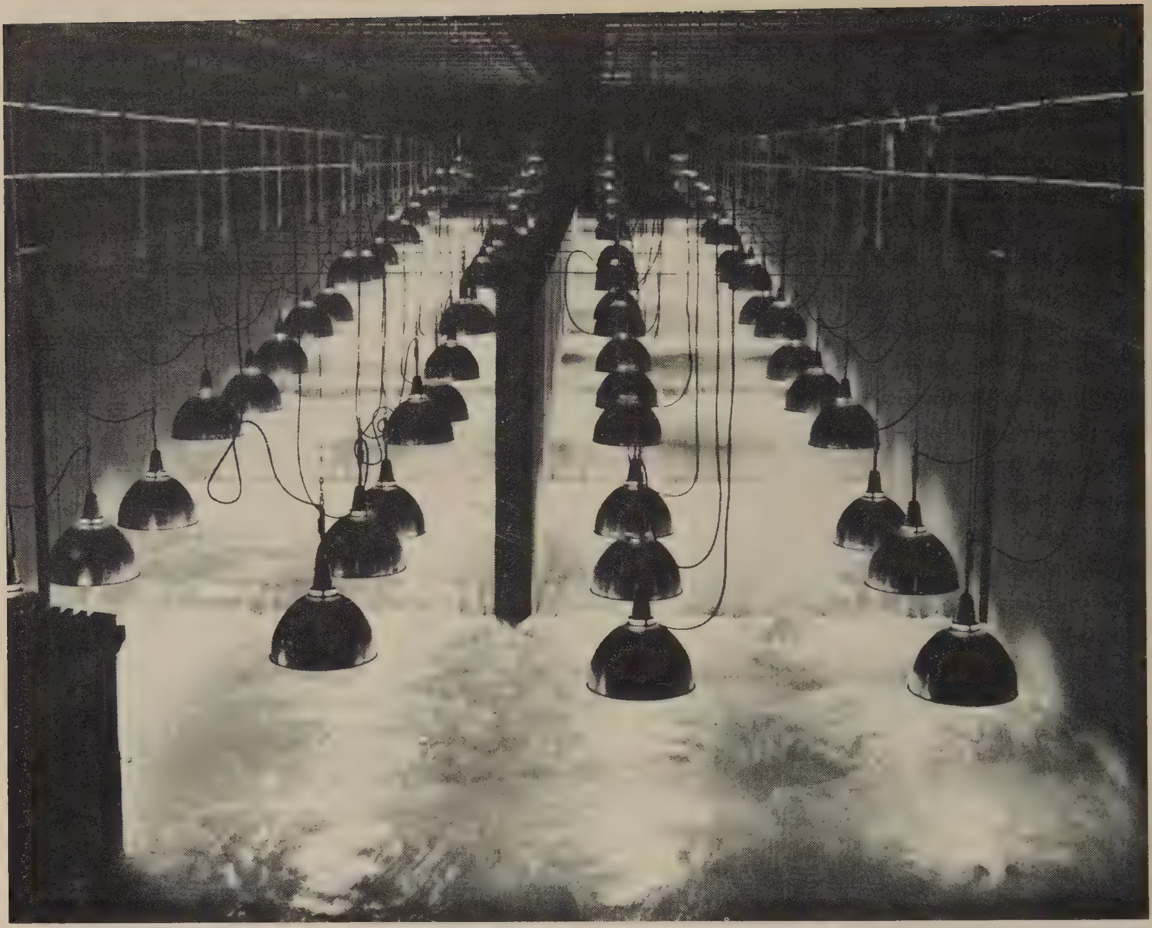


FIGURE 6.—Identical type-1 fishways with 1,000-watt mercury-vapor lights in place. Each light was 6 feet from the water surface.

the fish as it entered and left the fishway, thus obtaining total time spent in the fishway, which could be checked against the sum of the pool times. This method for timing individuals was used by Gauley (1960) for fishway slope experiments at Bonneville.

Groups

Rapid releases of individuals of the same species were made until 21-fish groups were introduced into each fishway. The releasing procedure was similar to that used for individual releases. Fish were released alternately into the test and control fishway until a total of 21 fish had been introduced into each fishway. Lengths were again noted for all fish that entered.

Passage time for group releases was recorded by a 20-pen recorder (fig. 8). The electrically operated recorder was used to tally on a chart all fish entering and leaving each fishway. When contact buttons were pressed at the counting station, a mark was made on the chart. A button at each counting station activated a different pen on the chart. Passage time of the fish was then determined from recorded chart times.

Two observers were stationed at the downstream and upstream ends of each fishway. At the lower end (weir 54) one counter tallied successful passages, while the second counter tallied fish that dropped back out of the test area.

Mass Releases

For these tests, fish were admitted to the introductory pool by raising a section of the picketed divider below each fishway. Thus a number could enter the control and test fishways simultaneously.

To control the number of fish entering, two sizes of release gates were used: A 10-inch wide

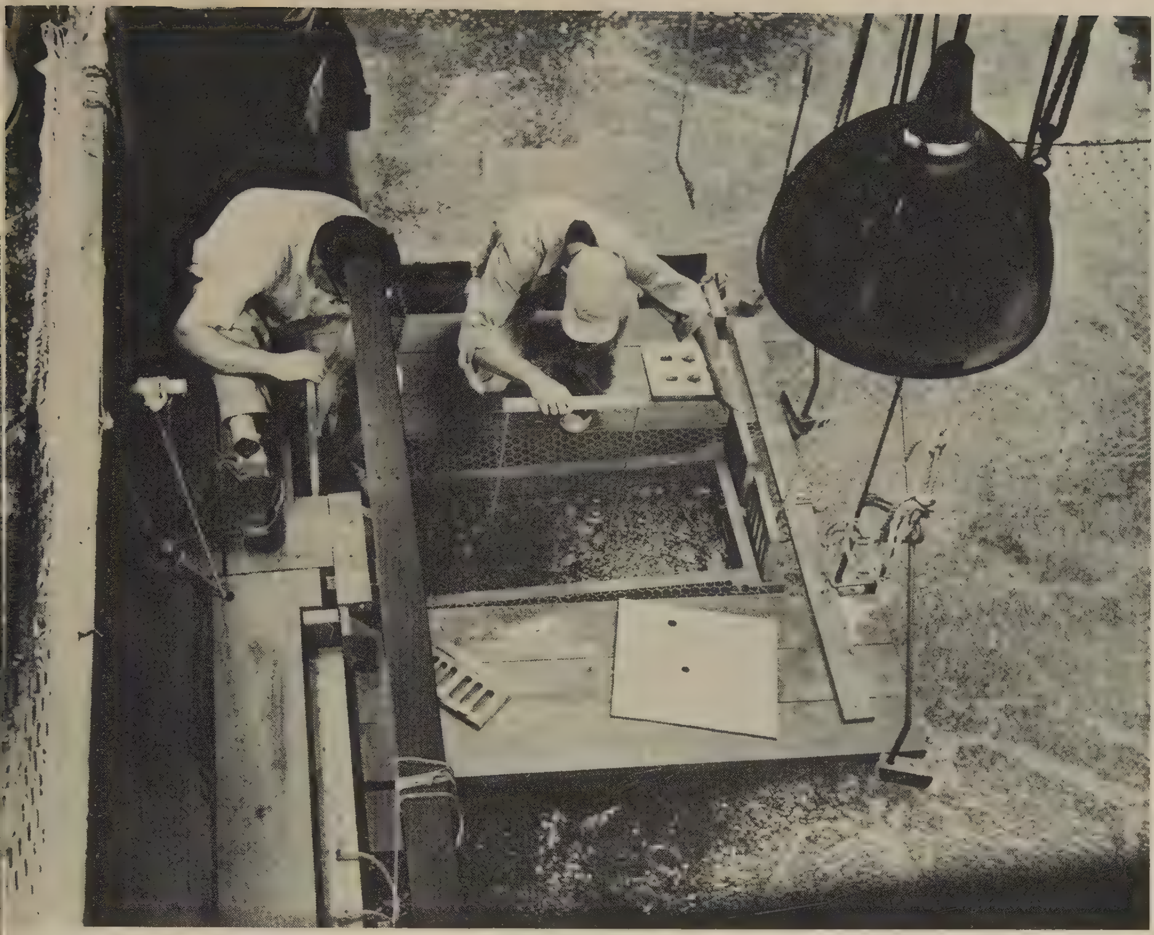


FIGURE 7.—The release compartment. The two exit gates are below the lamp reflector.

ing when fish were in ample supply and a t opening when fish were less plentiful.

e mass release timing procedure was essen- the same as that used for group releases. use mass releases were composed of mixed es, it was necessary to identify each fish as it he fishway at weir 60.

ANALYSIS OF PASSAGE TIMES

ssage time was used as a measure of perform- of salmonids in the different fishways tested. statistic employed and method of analysis d among individuals, groups, and mass re- s, depending on the adaptability of the data tistical treatment.

iduals

edian passage times of individuals were com- , and differences between fishways were mined by using 95 percent confidence intervals for the median (Dixon and Massey, 1951). Median passage times with the upper and lower limits are shown in table 2. The median was used in preference to the mean because of the high variance which generally occurred within the passage times in each fishway.

Groups

Both the median elapsed and the mean times were used to evaluate group (21 fish) passage times.

The median elapsed time is defined as the time differences between the median fish entering the fishway and the median fish existing at weir 60. This was determined simply by subtracting the time of the median fish over weir 54 from the time of the median fish over weir 60.

The application of median elapsed time to group releases occasionally appeared to be of limited value as a measure of passage time, because of aberrant values resulting when entry times into

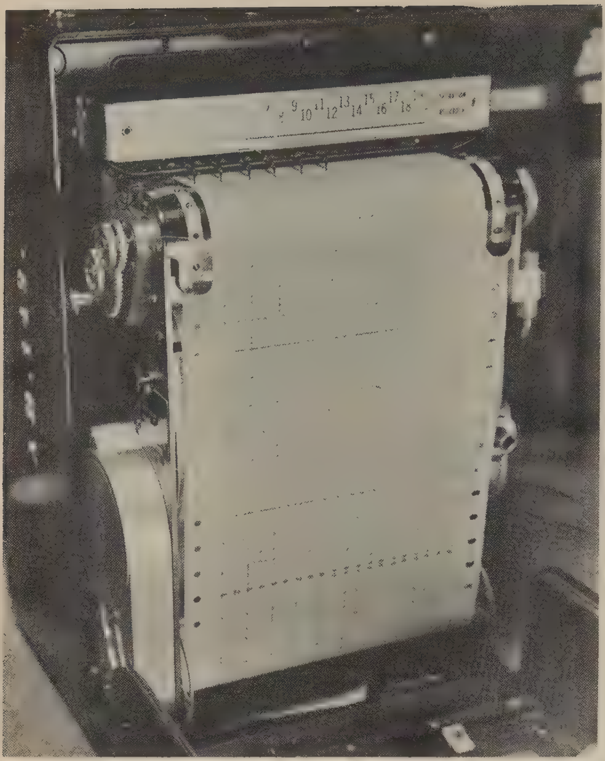


FIGURE 8.—The 20-pen operation recorder used to record passage times during group and mass releases. Six pens are in operation.

the release compartment were prolonged. This situation occurred only when fish were scarce or were reluctant to enter and pass through the release compartment. Consequently, the analysis of median elapsed time of group releases was limited to releases in which the introductory time was less than 1 hour.

The mean passage time is the difference between the mean time of the group over weir 54 and the mean time of the group over weir 60. In some instances it was necessary to assign an arbitrary exit time for individuals that did not cross weir 60.

If a fish had not passed weir 60 one hour after the last fish had gone over weir 54, one more hour was added and the resulting exit time was used in the determination of the mean exit time for al fish. Differences between passage times in the two fishways were tested by a *t* test on the means or medians at the 95 percent level.

Mass Releases

Mass releases were evaluated by comparing median elapsed times only. Again *t* tests were applied to determine if differences existed between the passage times of the test and control fishways. Here, *t* tests were applied to means of the median elapsed times.

The analysis of passage time for each mass release was accepted as being applicable to the dominant species of salmon. As pointed out earlier, however, mass releases included all species available so that the presence of minority species may have influenced the passage times during

TABLE 2.—*Median passage times with lower and upper limits of the 95 percent confidence intervals for chinook, sockeye, and steelhead individuals*

[Table A-25 Dixon and Massey, 1951]

Species	Date	Fishway type [1]	No. in sample	Passage time (minutes)		
				Lower limit	Median	Upper limit
Chinook:						
North	April 16–25	1	38	12.53	17.22	29.46
South		1	52	8.58	14.18	18.30
Test	May 15–16	[2] 1	13	3.47	6.23	24.73
Control		1	10	8.15	12.68	70.08
Test	April 29–May 7	[2] 1 B	69	4.65	6.22	9.02
Control		1	39	7.82	12.97	17.75
Test	May 31–June 7	2	74	7.33	9.88	12.03
Control		1	56	10.50	13.80	16.86
Test	June 12–July 9	3	46	9.73	15.10	31.37
Control		1	68	6.90	10.26	12.3
Sockeye:						
Test	July 12–18	2	111	1.20	1.40	1.90
Control		1	72	11.45	14.66	16.43
Test	June 13–July 9	3	65	7.85	12.30	15.42
Control		1	82	7.53	9.28	9.83
Steelhead:						
Test	April 29–May 7	[2] 1 B	10	5.90	11.26	15.08
Control		1	15	5.35	11.88	18.55
Test	May 31–June 6	2	8	4.12	9.98	28.97
Control		1	6	2.42	10.04	15.17
Test	June 12–July 9	3	33	2.95	6.68	11.22
Control		1	29	2.38	6.48	8.87

[1] See table 1.

[2] The Dalles-type weir crests installed.

e releases. This factor was not present during ridual and group releases.

RESULTS

1:16-SLOPE, 1.0-FOOT RISE

efore attempting to determine the effect of e on the rate of passage of salmonids, we gned an experiment to determine whether age times were the same in both channels of experimental flume. If passage times were l, then any difference found after slope had altered could be attributed to factors result- rom the difference in slope. Two conventional -slope fishways with a 1.0-foot rise between s were installed, one in each channel (fig. 9), a series of tests, using individuals, groups, mass releases, were conducted. Results are d mainly on chinook (*Oncorhynchus tshawytscha*), the dominant species in the fish run at the time the tests were conducted.

Thirty-eight individual chinook were tested in the north fishway and 52 in the south fishway. The median passage time was 17.22 minutes in the north fishway and 14.18 minutes in the south. Although the median time was slightly less in the south fishway, it was not significantly so.

Five groups of 21 chinook were timed in their passage through each fishway. The median elapsed passage times are given in table 3. A *t* test on the mean of the median elapsed times indicated there was no significant difference between the passage times in the two fishways.

The results of two mass releases comprised mainly of chinook (table 4) were similar to the individual and group tests which indicated that no difference existed between passage times in the two fishways.

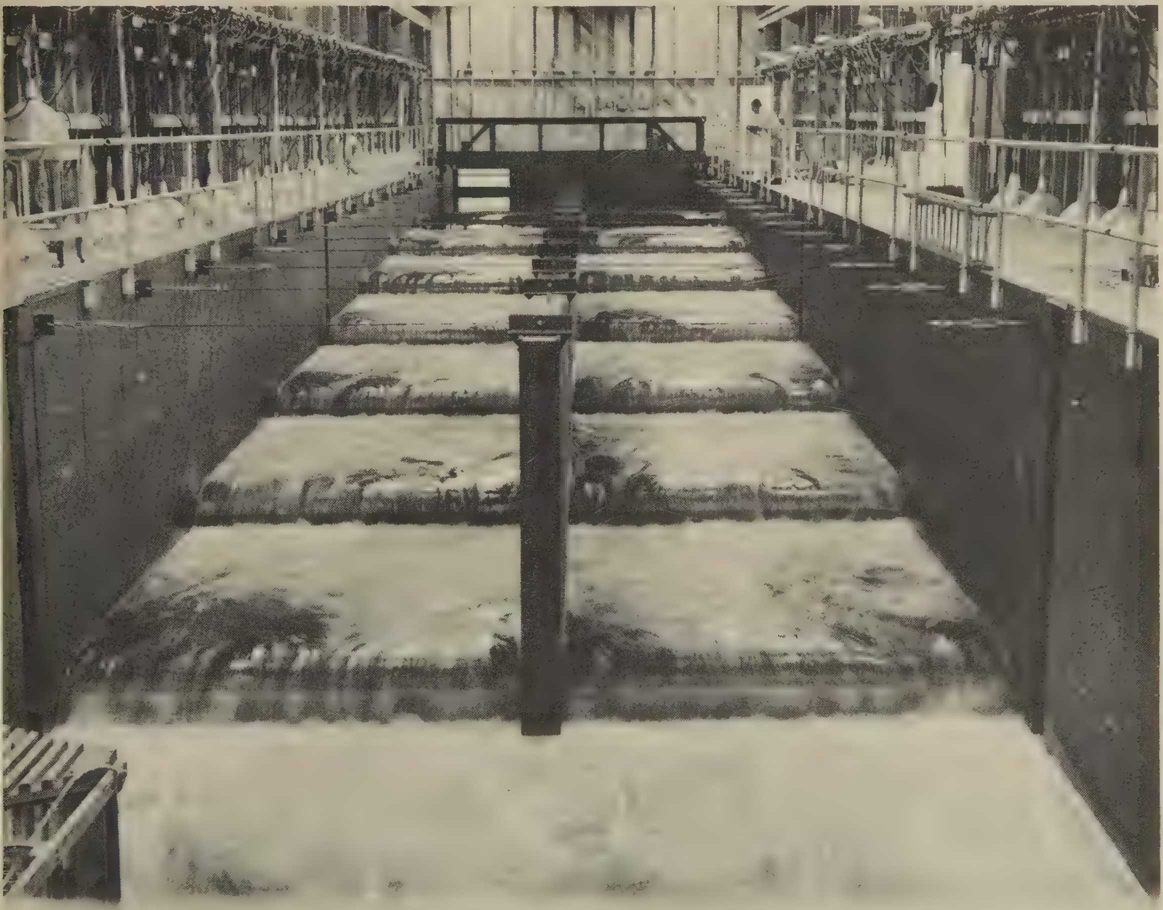


FIGURE. 9—Identical type-1 fishways used to test for equal passage times in the north (on the left) and south channels. The mercury-vapor lamps were removed to provide an unobstructed view of the fishways.

Table 3.—*Median elapsed passage times of 5 groups of 21 chinook in two type-1 fishways, Apr. 23–26, 1957*

Date	North fishway	South fishway
	Minutes	*Minutes*
Apr. 23	17.80	18.17
Apr. 24	13.02	24.78
Apr. 25	18.68	12.92
Do	15.43	16.75
Apr. 26	26.11	23.41
Mean	18.21	19.22

t .617
P >.05

1:8-SLOPE 1.0-FOOT RISE

Since the two sides (north and south) must be considered uniform on the basis of the tests, the 1:16-slope fishway in the north channel was removed and a 1:8-slope fishway with a 1.0-foot rise between pools (type 2) was installed (fig. 10). The south fishway was left unchanged to be used as the control fishway. Table 1 gives comparisons of the physical characteristics of the two fishways.

Table 4.—*Median elapsed passage times and species com position [1] of two mass releases in two type-1 fishways, Ap 19 and 26, 1957*

Date	North fishway			South fishway		
	Species composition		Median elapsed time	Species composition		Median elapsed time
	Chinook	Steelhead		Chinook	Steelhead	
	Number	*Number*	*Minutes*	*Number*	*Number*	*Minut*
Apr. 19	61	18	29.53	68	6	33.
Apr. 26	111	10	34.55	132	10	29.
Mean	----------	----------	32.04	----------	----------	31.

[1] Species identification was made as fish left the fishway at weir 60.

Chinook

Seventy-four individual chinook were timed i the test fishway and 56 in the control fishway fro May 31 to June 7. The median passage time were 9.88 and 14.00 minutes, respectively. A table of confidence intervals for the median indicates that the passage time was significantly les in the test fishway.

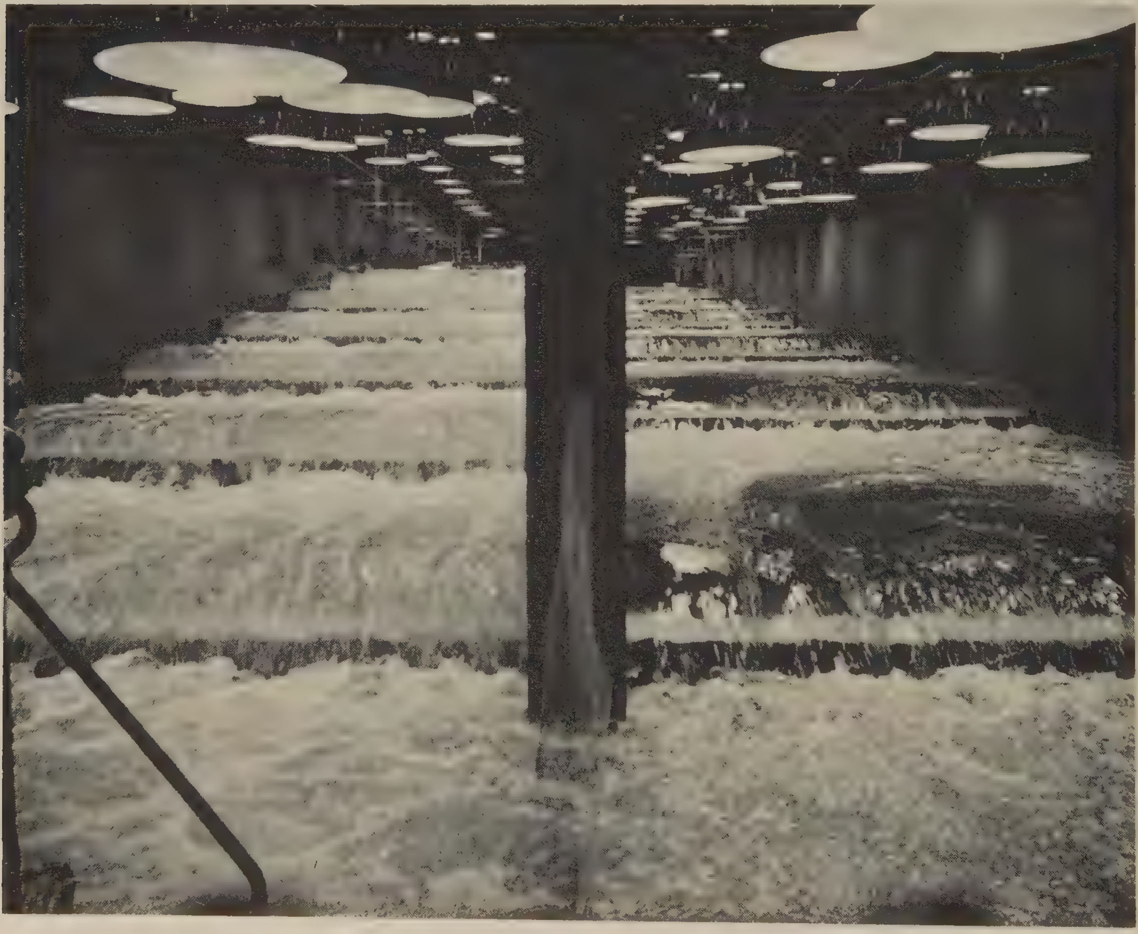


Figure 10.—A type-2 fishway on the left and a type-1 on the right. Note the greater turbulence in the type-2 fishway

LE 5.—*Median elapsed and mean passage times of 4 oups of 21 chinook timed in type 2 and type-1 fishways, ay 29 and June 5, 1957*

Date	Median elapsed time		Mean time	
	Test type-2 fishway	Control type-1 fishway	Test type-2 fishway	Control type-1 fishway
	Minutes	*Minutes*	*Minutes*	*Minutes*
29	11.37	12.33	8.28	18.70
o	15.08	14.60	20.20	19.05
o	19.57	19.19	17.73	15.27
5 [1]	----------	----------	17.79	13.05
Mean	15.34	15.37	16.00	16.52
t	.001		.299	
P	>.05		>.05	

edian elapsed times were not used because entry period exceeded 1 hour.

comparison of the median elapsed and mean sage times of four groups of 21 chinook timed ugh the test and control fishways is given in e 5. A *t* test on the means of the median sed times indicated there was no significant rence between passage times in the two fishs. Likewise, an analysis on the means of the n passage times gave similar results.

comparison of the median elapsed passage es of six mass releases comprised chiefly of ook salmon timed through the test and control ways is given in table 6. Species composition

LE 6.—*Median elapsed times of six mass releases tested type 2 and type-1 fishways, May 29 to June 7, 1957*

Date	Test type-2 fishway	Control type-1 fishway
	Minutes	*Minutes*
29	12.76	11.18
3	15.79	10.89
5	23.42	18.67
6	21.00	22.48
o	21.47	17.13
7	13.64	12.52
Mean	18.01	15.48
t	.952	
P	>.05	

hese releases is given in table 7. A *t* test on means of the median times indicated there was ignificant difference between the passage times he test and control fishways.

t the present time, we cannot offer an explana- for the difference between results obtained individual chinook passage times and chinook ased as a group and those released en masse. ividual passage times were significantly less he test fishway than in the control fishway, group and mass releases indicated no significant difference between passage times in the two fishways.

TABLE 7.—*Species composition* [1] *of mass releases tested in type 2 and type-1 fishways, May 29 to June 7, 1957*

Date	Test type-2 fishway			Control type-1 fishway		
	Chinook	Steelhead	Other [2]	Chinook	Steelhead	Other [2]
	Number	*Number*	*Number*	*Number*	*Number*	*Number*
May 29	65	3	----------	36	2	1
June 3	35	1	16	39	4	7
June 5	13	2	8	37	1	2
June 6	40	1	2	48	3	2
Do	67	1	----------	88	4	1
June 7	33	----------	1	29	2	1

[1] Species identification was made as fish left the fishway at weir 60.

[2] Mostly suckers (*Catostomus sp.*) and squawfish (*Ptychocheilus sp.*).

Sockeye

Tests were conducted on individual sockeye (Columbia River blueback) from July 12 through July 18. A scarcity of this species at this time precluded the use of group or mass releases for comparative purposes. Seventy-two sockeye were timed in the control fishway and 111 in the test fishway. The median times were 14.66 minutes and 1.40 minutes, respectively. Based on the confidence intervals about the medians, a significantly faster ascent was achieved in the test fishway than in the control. Note the striking differences in passage times between the two fishways. This difference was also apparent in the mean passage times (5.98 minutes in the test compared to 16.06 minutes in the control).

This rapid passage time in the test fishway gives rise to several questions. Would these fish react the same way in a longer fishway surmounting a dam? Could they continue at the same rate in a longer fishway, and if so, would this impair their ability to reach the upriver areas and spawn? Examination of these questions will be undertaken in future experiments.

Steelhead

Only 14 individuals were tested during May 31 to June 6, eight in the test fishway and six in the control fishway. The median times based on these small samples are 9.98 and 10.04 minutes respectively, indicating no difference between passage times.

Four mass releases were made in which steelhead comprised the principal species passed (table 8).

The median elapsed times in the test and control fishways are given in table 9. A *t* test on the

Table 8.—*Species composition [1] of four mass releases timed through type-2 and type-1 fishways, July 15–18, 1957*

Date	Test type-2 fishway				Control type-1 fishway			
	Chinook	Steelhead	Sockeye	Other [2]	Chinook	Steelhead	Sockeye	Other [2]
	Number	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
July 15	111	173	9	16	39	115	6	4
July 16	38	114	10	3	24	80	7	2
July 17	42	85	7	-------	12	77	8	3
July 18	25	111	12	6	9	67	3	2

[1] Species identification was made as fish left the fishway at weir 60.

[2] Carp (*Cyprinus* sp.), squawfish (*Ptychocheilus* sp.), and suckers (*Catostomus sp.*).

Table 9.—*Median elapsed times of four mass releases timed through type-2 and type-1 fishways, July 15–18, 1957*

Date	Test, type-2 fishway	Control, type-1 fishway
	Minutes	*Minutes*
July 15	8.98	16.02
July 16	9.22	11.59
July 17	7.75	12.23
July 18	6.50	13.75
Mean	8.11	13.35

t 4.492
P <.05

means of the median elapsed times for the two fishways indicated that the passage time through the test fishway was significantly less. This agrees with the conclusion drawn from research in 1956 (Gauley, 1960); groups of 20 steelhead ascended a similar test fishway in less time than they did the control fishway.

1:8-SLOPE, 1.5-FOOT RISE

In the following series of experiments the 1:8-slope fishway was modified to the condition employing 12-foot pools with a 1.5-foot rise between pools (type 3). It should be noted that an increase in rise between pools changes the flow over the weirs; water velocity increases, and water depth decreases. The control fishway remained unchanged (type 1). The two fishways are illustrated in figure 11.

Chinook

Individual passage times for two periods (June 12–20 and June 28 to July 9) were combined to provide a larger sample. This combination allows comparison of 46 individuals in the test fishway and 68 in the control fishway. The median time of chinook in the test fishway trials (15.10 minutes) was 5 minutes greater than the median time of the controls (10.26 minutes). Although there was approximately a 5-minute difference in passage times, this was not statistically significant.

Table 10.—*Median elapsed and mean passage times (minutes) of seven groups of 21 chinook tested in type-3 and type-1 fishways, June 13–19, 1957*

Date	Median elapsed time		Mean time	
	Test, type-3 fishway	Control, type-1 fishway	Test, type-3 fishway	Control, type-1 fishway
June 13	18.65	10.58	24.16	15.03
June 13 [1]	--------	--------	29.96	9.74
June 14	20.19	10.18	48.47	21.21
June 18	20.91	10.80	33.38	10.76
Do	17.40	13.25	37.23	10.02
June 19	18.28	16.05	17.79	14.76
Do	15.65	12.96	17.81	19.26
Mean	18.51	12.30	29.83	14.40

t 5.065 3.405
P <.05 <.05

[1] Median elapsed times were not used because entry period exceeded 1 hour.

The means of the median elapsed and the mean passage times for seven groups of 21 chinook are given in table 10. A *t* test on the means of the median elapsed times indicated that passage in the test fishway was significantly slower than in the control fishway. A similar analysis on the means of the mean passage times gave the same results.

Four mass releases, containing a preponderance of chinook, were made in the test and control fishways. Species composition for these releases are presented in table 11. Table 12 gives the

Table 11.—*Species composition [1] of four mass releases passing through type-3 and type-1 fishways, June 12 to July 1, 1957*

Date	Test type-3 fishway			Control type-1 fishway		
	Chinook	Steelhead	Sockeye	Chinook	Steelhead	Sockeye
	Number	*Number*	*Number*	*Number*	*Number*	*Number*
June 12	44	3	--------	49	5	--------
June 13	22	--------	--------	31	4	--------
June 19	79	3	3	116	18	12
July 1	24	8	9	42	14	14

[1] Species identification was made as fish left the fishway at weir 60.

Table 12.—*Median elapsed times (minutes) of four mass releases tested in type-3 and type-1 fishways, June 12 to July 1, 1957*

Date	Test type-3 fishway	Control type-1 fishway
June 12	23.85	20.72
June 13	18.46	17.36
June 19	25.75	11.05
July 1	27.97	23.01
Mean	24.01	18.04

t 1.798
P >.05

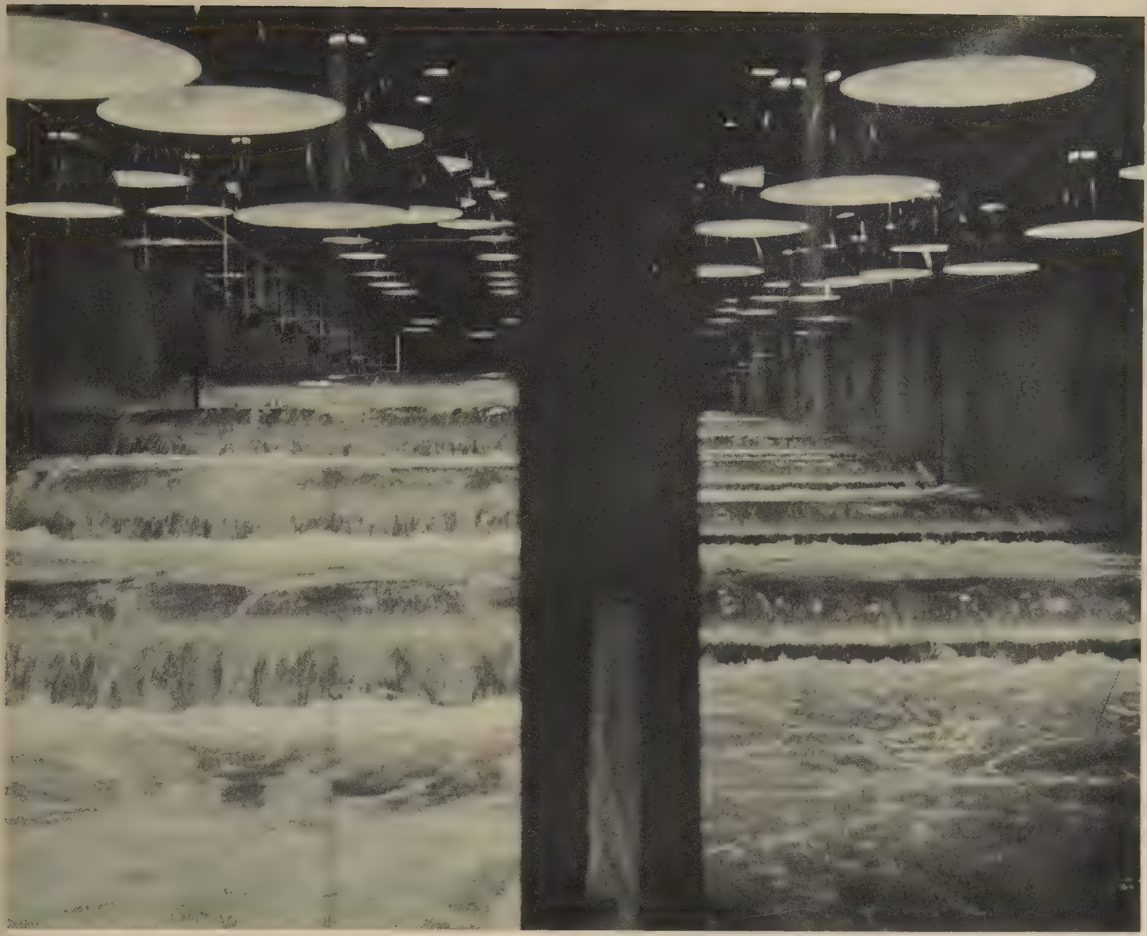


FIGURE 11.—A type-3 fishway (left) and a type-1 fishway (right).

dian elapsed times for four releases in the test l control fishways. In each of the four releases passage time was greater in the test fishway a *t* test on the means of the median elapsed es indicated no significant difference between sage times in the two fishways. Here, as was the case with individual chinook, passage es in the test fishway (type 3) were greater n in the control fishway (type 1) but not ificantly so.

keye

assage times of individual sockeye for the two ods June 13–20 and June 28 to July 9 were bined into a single sample as was done for ook. The median passage time of 66 sockeye e test fishway was 12.30 minutes while in the rol fishway the median time of 82 sockeye 9.28 minutes. Although the median time in test fishway was greater by 3 minutes, there was no significant difference between the passage times in the two fishways.

The median and mean passage times of five groups of sockeye are presented in table 13. Although the passage time was consistently greater in the test fishway, a *t* test on the means of the median elapsed times indicated there was no significant difference between passage times in the two fishways. A similar analysis on the means of the mean passage time gave the same results.

Steelhead

These tests comprised only the passages of individual fish. No group or mass releases were made. The passage time for the two periods June 12–20 and June 28 to July 9 were combined. The median passage times of 33 individuals in the test fishway and 29 in the control fishway were 6.68 minutes and 6.48 minutes, respectively. A comparison of these times indicated there was no

Table 13.—*Median elapsed and mean passage times (minutes) of five groups of 21 sockeye tested in type-3 and type-1 fishways, July 3–10, 1957*

Date	Median elapsed time		Mean time	
	Test type-3 fishway	Control type-1 fishway	Test type-3 fishway	Control type-1 fishway
July 3	17. 19	15. 20	25. 99	9. 64
July 5	25. 50	9. 09	17. 75	16. 02
July 8	15. 25	16. 19	25. 39	18. 05
July 9	16. 72	12. 56	14. 27	12. 12
July 10	37. 10	25. 78	34. 88	25. 80
Mean	22. 35	15. 76	23. 66	16. 33
t	1.330		1.615	
P	>.05		>.05	

significant difference in the passage time of steelhead in the test (type 3) fishway and the control (type 1) fishway. Previous experiments by Gauley (1960) yielded similar results.

Other Fish

At certain times during the summer fairly large numbers of carp, squawfish, and suckers ascend the Bonneville fishways. It is desirable to know how these species respond to different fishway conditions.

A mass release of June 18 contained a large percentage of squawfish and suckers. A total of 269 fish entered the control fishway, and approximately the same number passed through the fishway. These were identified as they passed out of the fishway at weir 60. Of the 269 fish, 159 (59 percent) were nonsalmonids. In the test fishway, of 196 entering, only 57 went out at weir 60. Of the 57 fish, seven (12 percent) were nonsalmonids. Assuming that equal proportions of nonsalmonids entered both fishways the suggestion is that the 1:8-slope fishway with a 1.5-foot rise between pools inhibits the passage of squawfish and suckers.

Other factors affecting passage time

Throughout the course of experiments and during the analysis of data on fishway passage times, it became apparent that factors other than fishway slope might have affected the passage time of salmonids through a given fishway. The supplementary nature of data concerning these factors preclude a thorough analysis. Numerous factors were considered, but to date only three—(1) the Dalles-type weir crest, (2) seasonal variation, and (3) rise between pools—have yielded enough information for a brief discussion.

The Dalles-Type Weir Crests

The Dalles-type weir crests (fig. 12) were installed in the south fishway in conjunction with other studies. This installation made possible the comparison of the fish-passing ability of this type of weir crest with the conventional square weir crests in the north fishway.[2] Chinook and steelhead individuals were timed through type-1 and type-1, *B* (fig. 13), fishways. (See table 1 for fishway dimensions.)

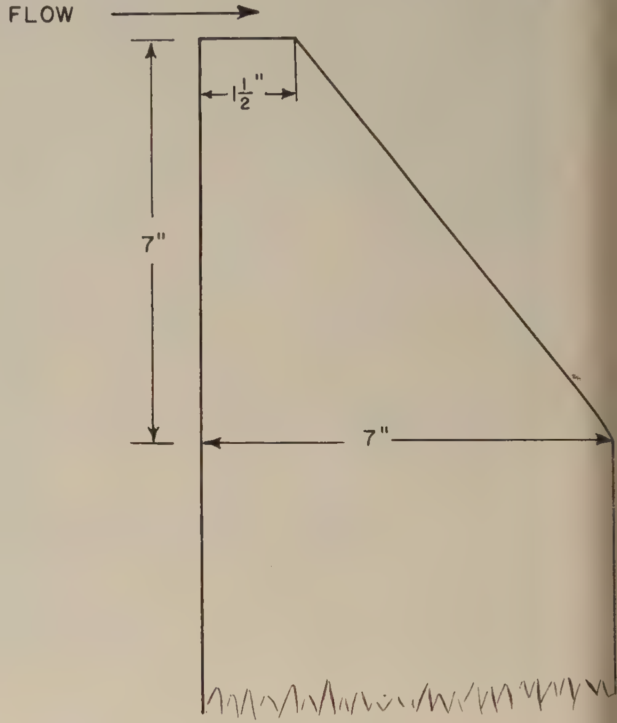


Figure 12.—Cross section view of the Dalles-type weir crest.

Three comparisons between the two weir crests and two fishway types, given in table 14, indicate the following with respect to chinook passage: Case 1—chinook moved faster in a 11.5-foot-wide fishway having Dalles-type weir crests than in a similar fishway having square weir crests; Case 2—chinook moved faster in a 4-foot-wide fishway having Dalles-type weir crests than in a fishway 11.5 feet wide having square weir crests; Case 3—there was no difference between chinook passage times in the wide and narrow fishways with the Dalles-type weir crest. Thus, in case 2, the ac-

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[2] Here, the Dalles-type weir crest is a sharp crested weir and the square weir crest is considered a broad crested weir. With equal heads on both weir types, the flow over the sharp crested weir will be approximately 10 percent greater.

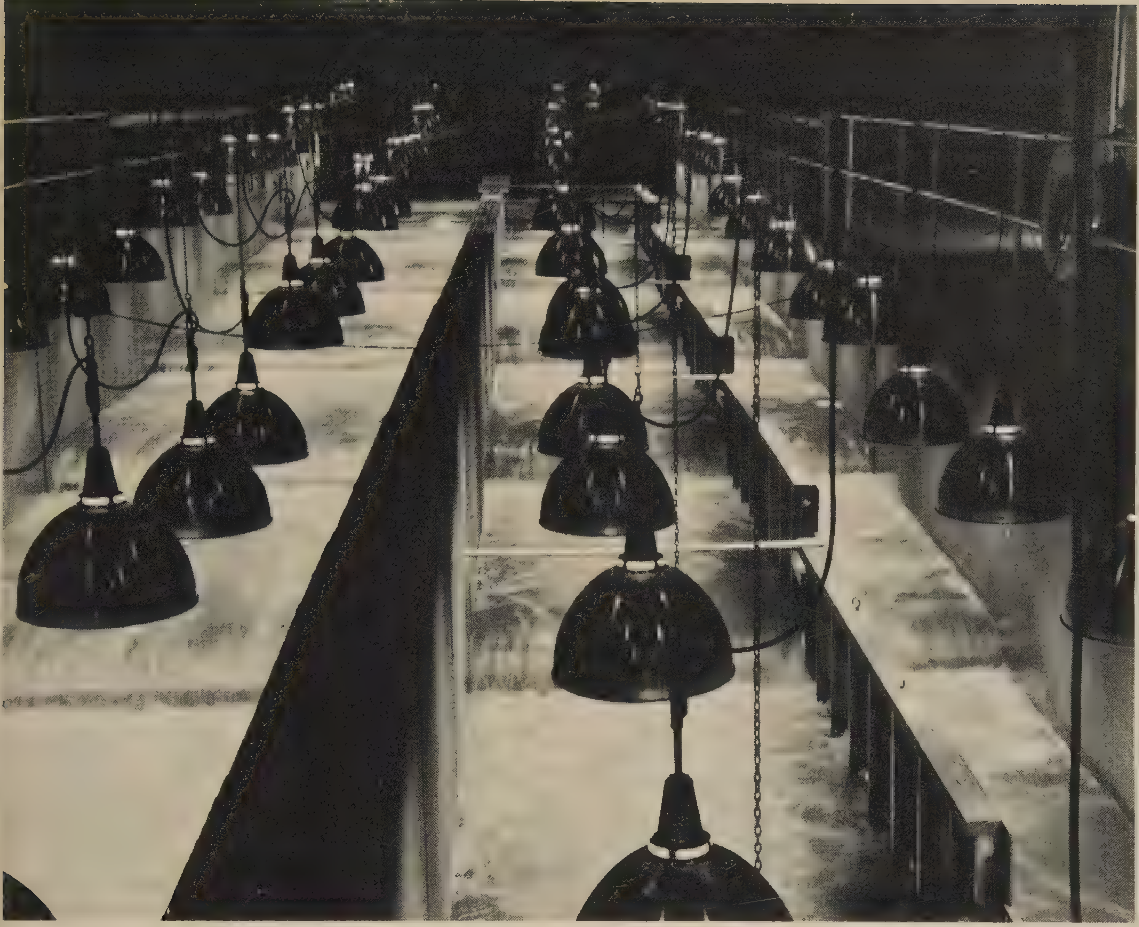

FIGURE 13.—The type-1, *B*-fishway (extreme right), created by installing a partition wall in a type-1 fishway.

LE 14.—*Comparisons between the Dalles-type and square pe weir crests using individual chinook passage times in pe-1 and type-1 B fishways, Apr. 29 to May 16, 1957*

	Fishway type	Sample size	Lower limit	Median	Upper limit
		Number of fish	*Minutes*	*Minutes*	*Minutes*
	Type 1, square crests	10	8.15	12.68	70.08
	Type 1, Dalles crests	13	3.47	6.23	24.73
	Type 1, square crests	39	7.82	12.97	17.75
	Type 1 B, Dalles crests	69	4.65	6.22	9.02
	Type 1, Dalles crests	13	3.47	6.23	24.73
	Type 1 B, Dalles crests	69	4.65	6.22	9.02

rated passage of chinook in the type-1, B way appears to have been a function of the es-type weir crests rather than fishway width. y contrast, a comparison between the passage s of 10 steelhead in a type-1, B fishway having es-type weir crests and 15 steelhead in a fishway having square crests, showed no rence between the median passage times in two fishways.

The Dalles-type weir crest appeared to be more advantageous for chinook passage than the square-type crest. Perhaps this is due to the greater flow of water over the sharp-crested weir, the oblique plane of the weir crest, or a combination of factors. The fact that steelhead were not accelerated by the Dalles-type crest suggests that some difference in species or size may affect an individual's ability to negotiate weir crests of different designs.

Seasonal Variation

Previous experiments in 1956 (Gauley, 1960) indicated there was a seasonal variation in passage time of steelhead through the control fishway. In the recent experiments, chinook and sockeye were examined to determine if this were also true for these species. Only passage times in the type-1 (control) fishway were used as this fishway was not altered and provided for passage time comparisons during most of the season.

Individual passage times were used to compare three periods of chinook migration, April 16 to May 7, May 31 to June 7, and June 12 to July 9, corresponding roughly to the spring run, an intermediate peak, and the summer run (fig. 14). The median passage times presented in table 15 indicate that individual chinook in the summer period (June 12 to July 9) moved significantly faster than during the other two periods.

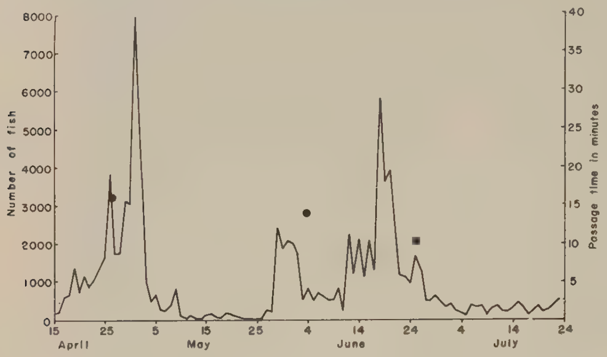

FIGURE 14.—The variation in median passage times (round dots) of chinook individuals during three segments of the run passing Bonneville Dam. The run (solid line) is represented by the daily counts in the Washington shore ladder, 1957. (Daily chinook count obtained from Corps of Engineers.)

TABLE 15.—*Median passage times of chinook tested in a type-1 fishway during three periods, Apr. 16 to July 9, 1957*

Date	Sample size	Lower limit	Median	Upper limit
	Number of fish	*Minutes*	*Minutes*	*Minutes*
Apr. 16–May 7	129	11.60	15.90	17.75
May 31–June 7	56	10.50	13.80	16.88
June 12–July 9	68	6.90	10.26	12.37

Group releases of chinook revealed basically the same result. An analysis of variance on the means of the median elapsed times (table 16) showed a significant difference between the means of the three periods.

Passage times of individual sockeye in a type-1 fishway are available for comparison throughout most of the run. For analysis, the passage times were divided into two groups: June 13 to July 5 and July 8–18, representing the first and last half of the sockeye run (fig. 15). A comparison of the median passage times presented in table 17 indicates that fish in the first part of the run were significantly faster than those in the last part of the run.

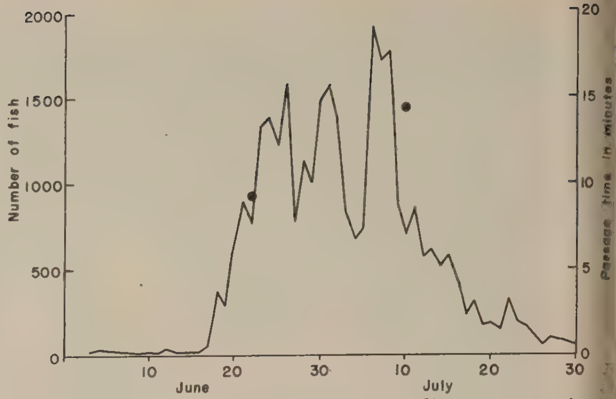

FIGURE 15.—The variation between median passage times (round dots) of sockeye individuals in the first half and the last half of the run passing Bonneville Dam. The run (solid line) is represented by the daily counts in the Washington shore ladder, 1957. (Daily sockeye count obtained from Corps of Engineers.)

TABLE 16.—*Median elapsed times (minutes) of groups of chinook tested in a type-1 fishway during three periods, Apr. 23 to June 19, 1957*

	April 23–26	May 29–June 7	June 13–19
	18.17	12.33	10.58
	24.78	14.60	17.61
	12.92	19.19	10.18
	16.75	12.90	10.80
	23.41		13.25
			16.05
			12.96
Mean	19.22	14.76	13.06

TABLE 17.—*Median passage times of two groups of sockeye tested in a type-1 fishway during June 13–July 18, 1957*

Date	Sample size	Lower limit	Median	Upper limit
	Number of fish	*Minutes*	*Minutes*	*Minutes*
June 13–July 5	73	6.00	9.22	11.58
July 8–18	80	11.28	14.30	16.28

Rise Between Pools

Research on a 1:8-slope fishway by Gauley (1960) indicated a direct relationship between magnitude of rise between pools and passage time. Recent supporting evidence was found by comparing passage times of chinook and sockeye in the 1:8-slope fishway with 1.0- and 1.5-foot rises, respectively.

The median passage times of sockeye individuals timed through type-2 and type-3 fishways are given in table 18. A comparison of these times showed that the passage time was significantly

LE 18.—*Median passage times of sockeye and chinook individuals ascending 1:8-slope fishways with a 1.5-foot rise (type-3 fishway) and a 1-foot rise (type-2 fishway) between pools*

[Passage times in the respective control fishways are included]

Species	Date	Test 1:8-slope					Control 1:16-slope				
		Rise	Sample size	Lower limit	Median	Upper limit	Rise	Sample size	Lower limit	Median	Upper limit
		Feet	*Number of fish*	*Minutes*	*Minutes*	*Minutes*	*Feet*	*Number of fish*	*Minutes*	*Minutes*	*Minutes*
ye	June 17–July 9	1.5	65	7.85	12.30	15.42	1.0	82	7.53	9.28	9.83
	July 12–18	1.0	111	1.20	1.40	1.90	1.0	72	11.45	14.66	16.43
ok	June 12–July 9	1.5	46	9.73	15.10	31.37	1.0	68	6.90	10.26	12.37
	May 31–June 7	1.0	74	7.33	9.88	12.03	1.0	56	10.50	13.80	16.88

in a fishway having a 1.0-foot rise than in a way having a 1.5-foot rise. Comparative s given for passage through the control vay suggest that the differences due to rise ld have been even more pronounced, if seasonal ation had been taken into account.

he median passage times of chinook individuals ype-2 and type-3 fishways are also presented able 18. Chinook ascending the type-2 fish- were faster than those ascending the type-3 vay but not significantly so. Again com- ng passage times in the control fishway, the rence would have been more pronounced if onal variation had been considered.

SUMMARY

he effects of fishway slope on the rate of pas- of chinook, sockeye, and steelhead were ied at the Fisheries-Engineering Research oratory at Bonneville Dam, by comparing age times of salmonids through two fishways different slopes—a 1:8-slope test fishway and 6-slope control fishway. Both fishways were -and-overfall type without submerged orifices, ning a total gain in elevation of 6 feet. Pas- times of individuals, groups, and mass re- s were used to compare fishway slopes and ental factors.

comparison of passage times between the 1:8- test fishway with a 1.0-foot rise between pools the 1:16-slope control fishway with a 1.0-foot between pools demonstrates that chinook, eye, and steelhead ascended the test fishway faster rate than the control fishway. The age times, however, were not always signifi- y faster.

hen the rise between pools in the test fishway increased to 1.5 feet, there was a corresponding increase in passage time. Most of the chinook, sockeye, and steelhead ascended the test fishway at a slower rate than the control fishway but only chinook groups were significantly slower.

Three incidental factors affected passage time: (1) weir crest design, (2) seasonal variation, and (3) rise between pools. Tests in the 1:16-slope fishway with Dalles-type weir crests and square weir crests showed chinook ascended the Dalles crest faster while steelhead ascents were about the same for both weir crest designs. A significant seasonal variation in passage times through fishways occurred within the respective chinook and sockeye salmon migrations. Chinook in the summer run were significantly faster than individuals in the spring run while the first half of the sockeye run was significantly faster than the last half. The median passage time of chinook and sockeye in a 1:8-slope fishway having a 1.0 foot rise between pools was significantly less than in the same fishway having a 1.5-foot rise between pools.

ACKNOWLEDGMENTS

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E, GROWTH, AND MATURITY OF ROUND WHITEFISH OF THE APOSTLE ISLANDS AND ISLE ROYALE REGIONS, LAKE SUPERIOR

By MERRYLL M. BAILEY, *Fishery Biologist*
BUREAU OF COMMERCIAL FISHERIES

ABSTRACT

he round whitefish has been of some commercial ortance in the upper Great Lakes but production ake Superior has generally been small; the United tes average was 26,600 pounds for 1929–59.

his study is based on 1,173 fish collected in the stle Islands in 1958–60 and 103 collected at Isle ale in 1958 and 1960. The average age of 6.0 years sle Royale was concluded to be significantly higher n the mean of 4.2 years in the Apostle Islands. The y-scale relation is a straight line with an intercept .1 inches on the length axis. Weight of Apostle nds round whitefish captured in several months in- ased as the 3.22 power of the length. Growth in th was relatively slow; nearly or fully 7 years were required to reach an acceptable commercial length of 14 inches in both the Apostle Islands and at Isle Royale. The calculated weights at the end of the seventh year were 12.6 ounces in the Apostle Islands and 13.8 ounces at Isle Royale. Minimum length at maturity of male round whitefish (7.0–7.4 inches) was less than that of females (8.5–8.9 inches). At age-group II, 11.1 percent of male round whitefish, but only 1.5 percent of the females were mature. All males were mature as age-group V and all females as age-group VI. Males dominated the younger age groups but females were more numerous in the older ones. Estimates of the number of eggs in 37 round whitefish ovaries yielded an average of 5,330 eggs for fish 10.5–17.4 inches long.

he round whitefish, *Prosopium cylindraceum*, ound in all the Great Lakes but Lake Erie. e species ranges north from the Great Lakes to Arctic, is present in the streams and lakes of tern Canada, and occurs in both the St. wrence and Hudson River drainages (Hubbs l Lagler, 1947).

he present study of age and growth is the first the round whitefish in Great Lakes waters, but wth studies of the species have been made for er waters by Cooper and Fuller (1945), nnedy (1949), and Rawson (1951). Information on the age and growth of the related pygmy tefish, *Prosopium coulteri*, in Lake Superior s published by Eschmeyer and Bailey (1955); s species has not been reported from any other he Great Lakes.

The round whitefish has some commercial importance. Greatest production has been in Lake Michigan (mostly in the northern part) where the annual catch frequently has approached or exceeded a quarter-million pounds. The U.S. waters of Lake Huron (limited data for Canadian waters) have also produced round whitefish, but the annual catch there has seldom exceeded 100,000 pounds. Production in Lake Superior generally has been small. The catch in U.S. waters of the lake averaged 26,600 pounds in 1929–59. The largest catch most commonly was taken in Michigan waters. The mean landings for the States were: Michigan, 13,600 pounds; Wisconsin, 9,400; Minnesota, 3,700. Production of round whitefish in Canadian (Ontario) waters of Lake Superior averaged 11,000 pounds in 1952–59 (no statistics on the species in earlier years).

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Substantial increases in 1959 U.S. landings (to 69,000 pounds), and the estimated 1960 Canadian catch of 58,000 pounds, could mark the beginning of an upward trend in Lake Superior round whitefish production.[1]

Despite the highly palatable flesh, the market value of the round whitefish has been limited because of the relatively small average size and the fluctuating supply. Small catches often are sold as part of shipments of other species. This marketing procedure may contribute to an underestimate of the production since "odd poundages" are not always listed by fishermen on their reports.

A major purpose of the present study was the gathering of information on the size, age composition, and growth of round whitefish in Lake Superior from which to judge the possibilities for increased exploitation.

MATERIALS AND METHODS

This study is based on 1,173 round whitefish collected at various localities in the Apostle Islands (fig. 1) area and 103 specimens captured off the southwestern end of Isle Royale during the operations of the U.S. Bureau of Commercial Fisheries research vessel *Siscowet* (fig. 1). The study is based mainly on the Apostle Islands collections; the small samples from Isle Royale, taken coincidentally to the major work of the *Siscowet* in that area, were collected to obtain information on the possibility of local differences of growth rate. The majority of fish were taken in nylon gill nets 300 feet long and 6 feet deep (table 1). Nine nets of graded mesh sizes (1 to 5 inches, stretched measure, by ½-inch intervals) were joined end to end and fished on the bottom as a standard gang, usually overnight. The remaining gill net samples were collected in shorter gangs of 2- to 3-inch mesh nets.

The sample of April 30, 1959, includes 36 fish of age-group I taken by a semiballoon otter trawl, 30 feet wide at the mouth, with mesh sizes of 2½ inches in the wings and body and ½-inch mesh in the cod end. Tows were made on the bottom in 5–15 fathoms.

The total length of each fish (tip of head to tip of tail, lobes compressed) was determined to the nearest 0.1 inch. Weights of fish 18 ounces or less were recorded to the nearest 0.1 ounce from a spring balance calibrated in 0.2-ounce intervals. Fish heavier than 18 ounces were weighed on a

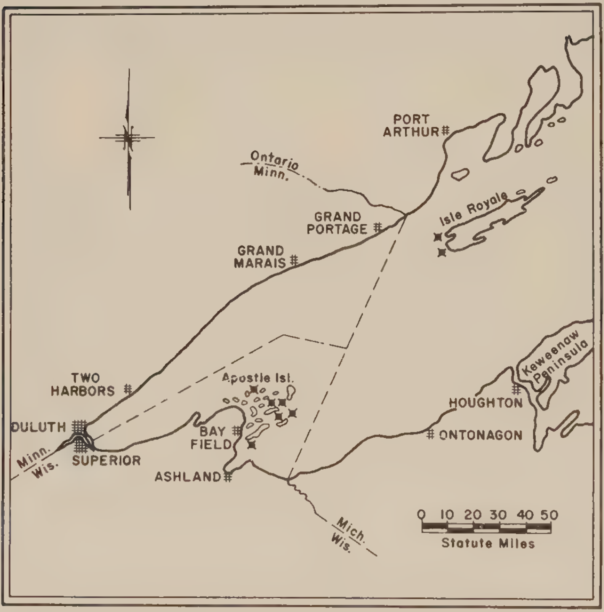

FIGURE 1.—Western Lake Superior. Dots with crosses represent sampling stations.

TABLE 1.—*Collections of round whitefish from the Apostle Islands and Isle Royale*

Locality and date	Gear			Total
	Gill net		Trawl	
	Standard gang [1]	Other [2]		
Apostle Islands:				
1958:				
June 5	73			73
July 9		32		32
July 23	180			180
Aug. 10–12		157		157
Oct. 24	79			79
Oct. 31	40			40
1959:				
Apr. 30	221		36	257
June 4	4			4
June 9	54			54
July 29	6			6
Oct. 19	40			40
Nov. 10	73			73
1960:				
Dec. 1	[3] 178			178
Isle Royale:				
1958:				
Aug. 20	65			65
1960:				
Aug. 9		38		38
Total:				
Apostle Islands	948	189	36	1,173
Isle Royale	65	38		103
Grand total	1,013	227	36	1,276

[1] Mesh sizes, 1 to 5 inches by ½-inch intervals.
[2] Various combinations of mesh sizes, 2 to 3 inches.
[3] Used only in determination of the length-weight relation (table 5).

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[1] The statistics for 1929–40 were taken from Gallagher and Van Oosten (1943); U.S. statistics after 1940 appeared in Lake Fisheries, issued by the U.S. Bureau of Commercial Fisheries. Canadian statistics were obtained from records of the Ontario Department of Lands and Forests.

milar balance calibrated to 0.1 pound. All eights obtained by this balance were later con- rted to ounces.

Sex and state of maturity were determined by oss examination of the gonads. A mature fish as one judged to be ready to spawn in the fall of at same year, regardless of whether it had awned previously.

Scales were removed from the left side of the fish idway between the lateral line and the base of the rsal fin. The scales were impressed in cellulose- etate strips by a roller press (Smith, 1954) and ere examined at the magnification X43. The ameters and growth fields within annuli of the ojected scales were measured in millimeters ong the longitudinal axis on a line passing rough the focus. Lengths at time of formation each annulus were determined nomographically om an empirically determined body-scale rela- on.

Ages were assessed by counting the number of nuli and are expressed in Roman numerals. sh were moved to the next higher age group on nuary 1 of each year. A virtual annulus ac- rdingly was assigned to the edge of the scale om that date until growth actually started. me difficulty was encountered in reading scales the older fish where the later annuli were in- stinct and close together. These annuli were rticularly hard to distinguish in the posterior ld of the scale. Only a few scales (less than 1 rcent) were discarded, however, as totally readable.

TIME OF ANNULUS FORMATION

Annulus formation for round whitefish in the ostle Islands differed slightly in 1958 and 1959. nulus formation was complete in 1958 for 32 rcent of the fish collected on June 5. All fish amined had completed an annulus at the time next collection on July 9. Fish captured on ne 9, 1959, showed no evidence of annulus rmation, but all of six fish captured on July 29 d completed the annulus. The period of an- lus formation for this stock appears, then, to l mostly in June but possibly may extend into rly July.

With the exception of two individuals caught ar Thompson Island on August 9, 1960, both nples from Isle Royale were taken at Rainbow ve, on the southern shore, one on August 20, 1958, and the other on August 9, 1960. All fish of the 1958 collection but only 32 percent of the fish caught in 1960 had completed the annulus. An annual difference of surface water temperatures (73.4° F. in 1958 but only 62.0° F. in 1960) could explain the difference.[2] Another possible factor could have been the greater proportion of older fish in the 1960 sample. It has been demonstrated (Hile, 1941) that younger fish form annuli earlier than do the older ones. Difficulty in deciding whether or not an individual fish had completed the annulus for the current season did not interfere with age determination.

AGE COMPOSITION

Round whitefish from the Apostle Islands and Isle Royale exhibited pronounced differences in age distribution and average age (table 2). Age-group IV was dominant at both localities, but Isle Royale had much the stronger representation of fish older than the VII group, and, conversely lacked entirely members of age-groups I and II. In the Apostle Islands the fish of age-groups I and II together made up more than 16 percent of the sample. As a result of these differences the mean age at Isle Royale (6.0 years) was 1.8 years greater than the average of 4.2 years for the fish from the Apostle Islands. The oldest fish taken belonged to age-group IX in the Apostle Islands and to age-group XII at Isle Royale.

An under representation of the younger round whitefish was to be expected at Isle Royale in 1960 since the gill nets fished that year had meshes too large to take numbers of age-groups I and II and may have sampled age-group III inefficiently. The standard gangs (mesh sizes 1 to 5 inches by ½-inch intervals) fished in 1958, however, failed to capture any I- or II-group individuals. It is clear, then, that the younger round whitefish were not on the grounds fished at Isle Royale in 1958. This situation could represent a summer segregation by age within round whitefish stocks generally, but more probable, it is peculiar to the Isle Royale locality. A standard gang lifted in the Apostle Islands on July 23, 1958, took 32 II-group individuals—17.8 percent of a total sample of 180. The only sizable August collection from the Apostle Islands—157 fish on August

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[2] Temperature data taken during the 1958 and 1960 operations of the U.S Bureau of Commercial Fisheries vessel *Siscowet*.

10–12, 1958—lacked young fish because of the larger mesh sizes, the same as those fished at Isle Royale in 1960. This collection included a single II-group fish. Each of these two summer collections from the Apostle Islands contained representatives of age-groups II–IX, inclusive. The gill nets were fully capable of taking older fish at both the Apostle Islands and Isle Royale.

It is concluded that the difference between the two stocks is real. Even if age-groups I and II were excluded from the Apostle Islands samples, the average age would be increased only to 4.6 years—still 1.4 years below the mean for Isle Royale. No definite explanation is offered for the differences in age distribution and average age of round whitefish in the Apostle Islands and at Isle Royale. Differences in natural mortality and in fishing mortality both may have been factors.

Table 2.—*Age composition of round whitefish taken in gill nets in the Apostle Islands and at Isle Royale*

Age group	Apostle Islands		Isle Royale	
	Number	Percentage	Number	Percentage
I	[1] 3	0.3	-----	-----
II	152	15.8	-----	-----
III	190	19.8	12	11.7
IV	270	28.2	24	23.3
V	130	13.6	13	12.6
VI	111	11.6	16	15.5
VII	66	6.9	9	8.7
VIII	27	2.8	10	9.7
IX	10	1.0	11	10.7
X	-----	-----	6	5.8
XI	-----	-----	1	1.0
XII	-----	-----	1	1.0
Total	959	-----	103	-----
Average age	4.2	-----	6.0	-----

[1] Fish taken in trawls included 36 additional members of age-group I.

The records of age composition for individual years at the two locations (not given here) offered no indication of the occurrence of exceptionally strong or weak year classes.

LENGTH DISTRIBUTION AND AVERAGE LENGTH OF AGE GROUPS

To avoid bias from the capture of fish at various times in the growing season, the data on the length distributions of the age groups (tables 3 and 4) are based on the calculated lengths at the time of formation of the last annulus. All samples for which age was determined have been used in the tables.

The distributions of I- and II-group round whitefish from the Apostle Islands did not overlap, but those of all other successive age groups overlapped from 2 to 4 inches. The range of length in the well-represented age groups was fairly large for fish that do not attain a great size. Among age-groups II–VIII it fell within the limits of 3 to 5 inches. The shortest range (2.5 inches) in age-groups I and IX can be attributed partly to the small numbers of fish.

Because of the overlap of the length distributions of age groups in the Apostle Islands, most of the 0.5-inch length intervals included fish of several ages. Every length between 7.0 and 15.9 inches was represented by at least two age groups, and five groups were included at 14.0–14.4 inches.

The length distributions of age groups of round whitefish from Isle Royale were similar to those of the Apostle Islands fish, except that the ranges were generally smaller and the overlap correspondingly less extensive. The difference in range can be explained by the small numbers of fish in the Isle Royale collections.

The average lengths of the age groups require little comment since more extensive data on

Table 3.—*Length distribution of age groups of round whitefish from the Apostle Islands*

[Based on calculated lengths at last annulus]

Total length (inches)	Age group									Total
	I	II	III	IV	V	VI	VII	VIII	IX	
3.0–3.4	1	-----	-----	-----	-----	-----	-----	-----	-----	-----
3.5–3.9	4	-----	-----	-----	-----	-----	-----	-----	-----	4
4.0–4.4	19	-----	-----	-----	-----	-----	-----	-----	-----	19
4.5–4.9	13	-----	-----	-----	-----	-----	-----	-----	-----	13
5.0–5.4	2	-----	-----	-----	-----	-----	-----	-----	-----	2
5.5–5.9	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
6.0–6.4	-----	6	-----	-----	-----	-----	-----	-----	-----	6
6.5–6.9	-----	33	-----	-----	-----	-----	-----	-----	-----	33
7.0–7.4	-----	79	3	-----	-----	-----	-----	-----	-----	82
7.5–7.9	-----	29	5	-----	-----	-----	-----	-----	-----	34
8.0–8.4	-----	4	42	-----	-----	-----	-----	-----	-----	46
8.5–8.9	-----	1	46	2	-----	-----	-----	-----	-----	49
9.0–9.4	-----	-----	41	13	-----	-----	-----	-----	-----	54
9.5–9.9	-----	-----	22	30	-----	-----	-----	-----	-----	52
10.0–10.4	-----	-----	21	65	-----	-----	-----	-----	-----	86
10.5–10.9	-----	-----	6	54	13	1	-----	-----	-----	74
11.0–11.4	-----	-----	4	40	22	1	-----	-----	-----	67
11.5–11.9	-----	-----	-----	38	35	3	-----	-----	-----	76
12.0–12.4	-----	-----	-----	21	33	13	-----	-----	-----	67
12.5–12.9	-----	-----	-----	6	18	36	2	-----	-----	62
13.0–13.4	-----	-----	-----	1	5	29	8	-----	-----	43
13.5–13.9	-----	-----	-----	-----	3	20	30	-----	-----	53
14.0–14.4	-----	-----	-----	-----	1	3	18	5	2	29
14.5–14.9	-----	-----	-----	-----	-----	3	6	10	-----	19
15.0–15.4	-----	-----	-----	-----	-----	2	1	7	2	12
15.5–15.9	-----	-----	-----	-----	-----	-----	1	4	2	7
16.0–16.4	-----	-----	-----	-----	-----	-----	-----	-----	4	4
16.5–16.9	-----	-----	-----	-----	-----	-----	-----	1	-----	1
Total number of fish	39	152	190	270	130	111	66	27	10	995
Average length (inches)	4.3	7.1	9.0	10.7	12.0	13.0	14.0	15.0	15.5	[1] 10.4

[1] Grand average length.

TABLE 4.—*Length distribution of age groups of round whitefish from Isle Royale*

[Based on calculated lengths at last annulus]

Total length (inches)	Age group										Total
	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
9	4										4
4	2										2
9	5										5
4	1	3									4
9		5									5
10.4		5									5
10.9		7									7
11.4		4	1								5
11.9			4								4
12.4			3								3
12.9			3	1							4
13.4				3	1						4
13.9			2	8	3						13
14.4				3	4						7
14.9				1	1	6	1				9
15.4						3	1	1			5
15.9						1	2	2			5
16.4							7	2			9
16.9								1			1
17.4										1	1
17.9									1		1
Total number of fish	12	24	13	16	9	10	11	6	1	1	103
Average length (inches)	8. 3	10. 4	12. 3	13. 7	14. 0	15. 0	15. 9	16. 0	17. 8	17. 3	[1] 12. 7

[1] Grand average length.

wth are offered in the later section on calculated wth. Attention is called, however, to the rela- ely slow growth in both stocks. Nearly or fully ears were required at each locality for the fish reach an average length of 1 foot, and the high- average length for any age group was not great .5 inches, IX group in the Apostle Islands; 17.8 hes, XI group at Isle Royale). Apostle Islands were the longer in age-groups III and IV, but he higher ages (V–IX) the mean lengths of the Royale stock equalled or exceeded those of of corresponding age in the Apostle Islands.

LENGTH-WEIGHT RELATION

he general parabola $W=cL^n$, where $W=$ weight, length, and c and n are empirically ermined constants, was used to describe the eral length-weight relation of round whitefish ble 5). Determination of the length-weight tion was based on data from 755 fish, captured he Apostle Islands during the 1958–60 collect- seasons, combined without regard to sex, state naturity, or time of collection. Lengths and pirical weights are averages for 0.5-inch inter- s of length. Since some 0.5-inch intervals had ge numbers of individuals, not all of the 1,173 stle Islands fish were used. The 178 fish cap- ed in the Apostle Islands in December 1, 1960, e included to strengthen the data at the higher gth intervals. These fish were not used else- ere in this study. Limited comparisons according to sex, state of maturity, and date of capture revealed two significant differences. Ripe fish of both sexes were slightly heavier than spent individuals, and fish taken during July and August were generally heavier than those captured in April or November.

TABLE 5.—*Length-weight relation of round whitefish from the Apostle Islands*

[The lengths and empirical weights are averages by 0.5-inch intervals of length. The calculated weights were computed from the equation given in the text]

Number of fish	Total length (inches)	Weight (ounces)		Number of fish	Total length (inches)	Weight (ounces)	
		Empirical	Calculated			Empirical	Calculated
1	4. 2	0. 3	0. 3	37	11. 7	6. 7	7. 0
2	4. 8	. 4	. 4	37	12. 2	7. 7	8. 1
2	5. 2	. 6	. 5	37	12. 7	8. 8	9. 2
3	5. 7	. 8	. 7	37	13. 2	10. 4	10. 4
5	6. 3	. 9	1. 0	37	13. 7	11. 8	11. 7
33	6. 8	1. 1	1. 2	37	14. 2	13. 3	13. 1
37	7. 2	1. 3	1. 5	37	14. 7	14. 8	14. 7
25	7. 7	1. 7	1. 8	37	15. 1	17. 1	16. 0
27	8. 2	2. 2	2. 2	31	15. 7	19. 6	18. 2
37	8. 7	2. 6	2. 7	19	16. 1	22. 0	19. 7
37	9. 2	3. 0	3. 2	21	16. 7	22. 8	22. 2
37	9. 7	3. 6	3. 9	15	17. 1	25. 6	23. 9
37	10. 1	4. 2	4. 4	9	17. 7	27. 6	26. 7
37	10. 7	4. 9	5. 3	7	18. 1	29. 0	28. 7
37	11. 2	5. 9	6. 1				

The length-weight equation, determined by fitting a straight line to the logarithms of the length and weight was:

$$\log W = -3.40468 + 3.2231 \log L,$$

where $W=$ weight in ounces,

and $L=$ total length in inches.

This equation may also be written in the form,

$$W=3.9384\times10^{-4}L^{3.2231}$$

The weights computed for the mean lengths of fish in each length interval are the basis of the curve in figure 2.

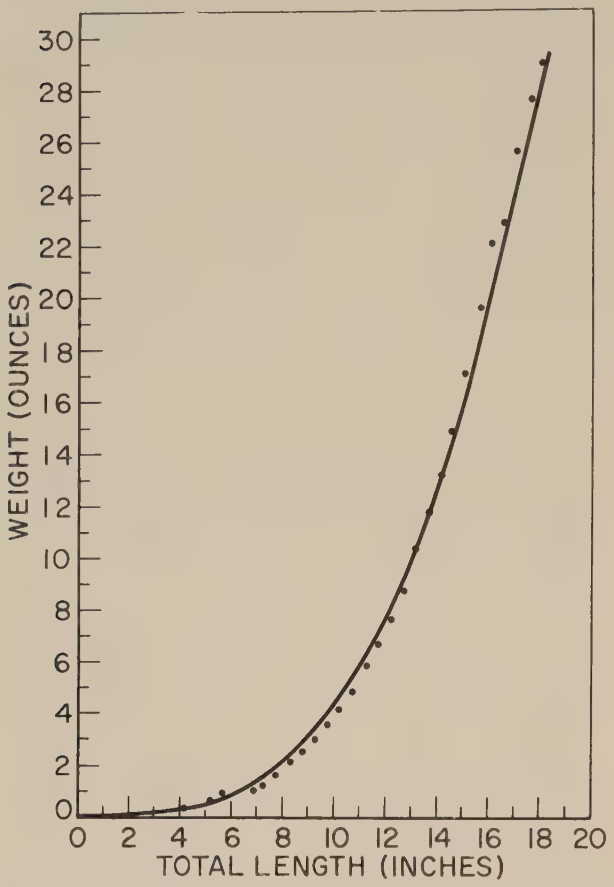


Figure 2.—Length-weight relation of round whitefish from the Apostle Islands. The curve represents the calculated weights and the dots, the empirical weights.

A direct comparison of empirical weights of Isle Royale and Apostle Islands round whitefish captured in August (details not given here) demonstrated almost no differences. It is suspected that the condition of the species is at its peak in August, as has been established for other coregonids—*Leucichthys kiyi* (Deason and Hile, 1947) and *Coregonus clupeaformis* (Van Oosten and Hile, 1949). The agreement between Apostle Islands and Isle Royale fish caught in the same month suggests that the length-weight equation derived for Apostle Islands fish may hold reasonably well for both stocks. The equation based on Apostle Islands fish caught in various months may be more suitable for the Isle Royale stock than one based on limited data for a single month in the latter area. The equation is accordingly applied to calculated lengths of both stocks in a later section on calculated growth in weight.

CALCULATED GROWTH

BODY-SCALE RELATION

The body-scale relation for round whitefish of the Apostle Islands area was determined from 429 specimens collected in 1958 and 1959 (table 6). Scale diameters were recorded only from the scale used in age determination. Care was taken, however, to read and measure a scale of average size after all scales on the slide were examined. A plot of the average fish lengths for 0.5-inch groupings, against the average scale diameters, indicated that a straight line best fitted the data (fig. 3).

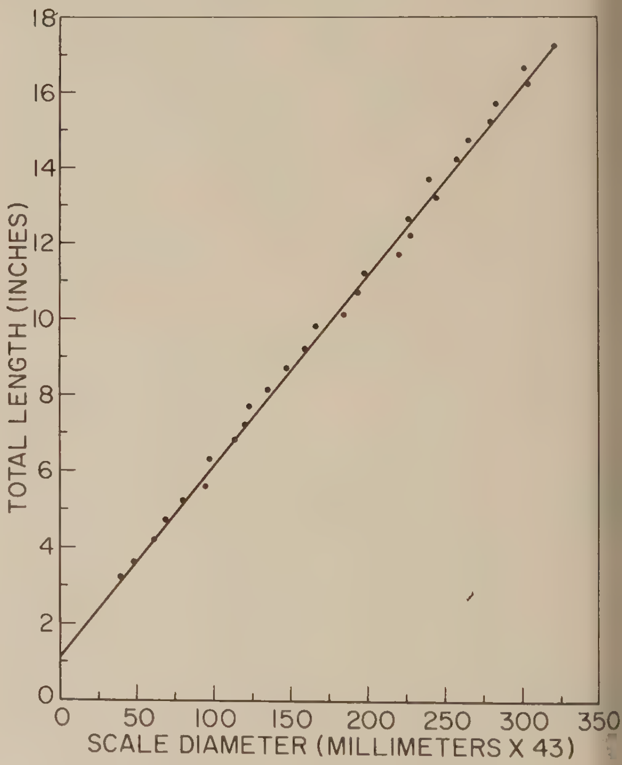


Figure 3.—Relation between total length of fish an magnified (X43) scale diameter for round whitefis from the Apostle Islands. [The dots represent th empirical data; the line is a graph of the equation give in the text.]

e equation for the line, fitted by least squares, is:

$$L = 1.1049 + 0.050\ S,$$

ere L=total length of the fish (inches),
d S=scale diameter (X43, in millimeters).

r practical purposes the intercept was taken to 1.1 inches. Lengths at formation of each nulus were calculated nomographically.

GROWTH IN LENGTH

The average calculated lengths of round white- gave no evidence of differences according to or date of capture. Consequently all collecns were combined at each locality in the preption of tables 7 and 8.

The calculated growth histories of the age groups eal both random and systematic discrepancies. ne of the randomly distributed discrepancies y reflect true differences of growth, but many of them can be attributed to the small numbers of fish in certain age groups, especially at Isle Royale. The systematic discrepancies are in the form of a progressive decrease of calculated lengths with increase in the age of the fish on which the calculations were based.

In the Apostle Islands samples (table 7) it is difficult to find a trend in the first-year calculated lengths. True, the oldest fish (IX group) had the shortest calculated length (3.7 inches) but this average was based on only 10 fish. The first-year length of the better-represented VIII group (4.4 inches; 27 fish) exceeded that of the younger age-groups I, VI, and VII, and equaled the value for age-group V. Only age-groups II, III, and IV had higher first-year lengths (all 4.8 inches). The second- and third-year calculated lengths, on the other hand, showed pronounced, though irregular downward trends with increase of age. All second-year lengths, for example, were above 7.0 inches (7.2 to 7.4 in age-groups II–V) but were under 7.0 inches (6.1 to 6.8) in age-groups VI–IX. Similarly, third-year lengths exceeded 9.0 inches (9.1 to 9.3) in age-groups III–V, but were lower (8.2 to 8.9 inches) in age-groups VI–IX. Beyond the third year of life no clear trends of calculated length with increase of age can be established.

The tendency for calculated lengths to decline with increase in the age of the fish on which the calculations were based is much clearer in the records for round whitefish from Isle Royale and extends to a greater number of years of life (table 8). As was true for Apostle Islands fish, no clear trend is apparent in the first-year calculated lengths. The calculated lengths for years 2–7, on the contrary, exhibited a clear, though frequently

LE 6.—*Relation between total length of fish and magnified X43) scale diameter for round whitefish from the Apostle slands*

ber of fish	Average length [1] (inches)	Average scale diameter (millimeters)	Number of fish	Average length [1] (inches)	Average scale diameter (millimeters)
	3.2	39	19	11.2	198
	3.6	48	19	11.7	222
	4.2	61	19	12.2	228
	4.7	69	19	12.6	228
	5.2	81	19	13.2	245
	5.6	95	19	13.7	241
	6.3	98	19	14.2	259
	6.8	114	19	14.7	266
	7.2	121	19	15.2	281
	7.7	124	15	15.7	284
	8.1	136	8	16.2	305
	8.7	149	8	16.6	302
	9.2	160	3	17.2	321
	9.8	167	1	17.6	290
	10.1	185	3	18.1	320
	10.7	194	2	18.6	303

ean for fish within a 0.5-inch length interval.

LE 7.—*Calculated total length at end of each year of life of each age group of round whitefish from the Apostle Islands and average growth for the combined age groups*

[Collections of 1958 and 1959 combined]

Age group	Number of fish	Length (inches) at end of year								
		1	2	3	4	5	6	7	8	9
	39	4.3								
	152	4.8	7.2							
	190	4.8	7.3	9.1						
	270	4.8	7.4	9.3	10.8					
	130	4.4	7.2	9.2	10.9	12.1				
	111	4.2	6.8	8.9	10.8	12.2	13.1			
	66	4.0	6.5	8.6	10.6	12.0	13.2	14.0		
	27	4.4	6.7	8.8	10.6	12.1	13.3	14.2	15.0	
	10	3.7	6.1	8.2	10.2	11.9	12.9	14.0	14.8	15.5
Grand average calculated length		4.6	7.2	9.1	10.8	12.1	13.1	14.1	14.9	15.5
Increment of average		4.6	2.6	1.9	1.7	1.3	1.0	1.0	0.8	0.6
Grand average increment of length		4.6	2.6	1.9	1.7	1.3	1.0	0.9	0.8	0.7
Sum of average increment		4.6	7.2	9.1	10.8	12.1	13.1	14.0	14.8	15.5

TABLE 8.—*Calculated total length at end of each year of life of each age group of round whitefish from Isle Royale and average growth for the combined age groups*

[Collections of 1958 and 1960 combined]

Age group	Number of fish	Length (inches) at end of year											
		1	2	3	4	5	6	7	8	9	10	11	12
III	12	3.6	6.1	8.4	--------	--------	--------	--------	--------	--------	--------	--------	--------
IV	24	3.4	6.3	8.7	10.5	--------	--------	--------	--------	--------	--------	--------	--------
V	13	3.6	6.3	8.7	10.7	12.3	--------	--------	--------	--------	--------	--------	--------
VI	16	3.3	6.0	8.6	10.8	12.7	13.8	--------	--------	--------	--------	--------	--------
VII	9	3.3	6.0	8.1	9.9	11.7	12.9	14.0	--------	--------	--------	--------	--------
VIII	10	3.3	5.5	7.8	9.9	12.0	13.4	14.3	15.1	--------	--------	--------	--------
IX	11	3.5	6.0	8.2	10.3	12.0	13.4	14.3	15.2	15.9	--------	--------	--------
X	6	3.0	5.3	7.5	9.2	11.2	12.7	13.8	14.7	15.3	16.0	--------	--------
XI	1	3.3	5.1	7.3	9.0	11.1	12.7	13.9	15.4	16.5	17.3	17.8	--------
XII	1	3.5	5.6	7.3	9.0	10.4	11.6	12.6	13.9	14.8	16.1	16.6	17.3
Grand average calculated length	--------	3.4	6.0	8.4	10.3	12.1	13.3	14.1	15.0	15.7	16.2	17.2	17.3
Increment of average	--------	3.4	2.6	2.4	1.9	1.8	1.2	0.8	0.9	0.7	0.5	1.0	0.1
Grand average increment of length	--------	3.4	2.6	2.3	2.0	1.8	1.3	1.0	0.9	0.7	0.8	0.5	0.7
Sum of average increment	--------	3.4	6.0	8.3	10.3	12.1	13.4	14.4	15.3	16.0	16.8	17.3	18.0

interrupted, tendency to decrease with increase of age. Beyond the seventh year, trends cannot be established—partly, perhaps, because of the small numbers of fish in the older age groups.

Systematic discrepancies in the calculated growth histories of different age groups are common in data on growth of fish. The most likely contributing factors for these discrepancies for Apostle Islands and Isle Royale round whitefish are: biased samples from gear selection; selective destruction of the faster growing fish in the fishery; higher natural mortality for fish with rapid growth than for those with slow growth.

Certain samples almost surely were biased from gear selection. As was recorded in table 1: 189 fish from the Apostle Islands and 38 from Isle Royale were taken in gangs of gill nets that included no mesh sizes under 2 inches. This gear would select only the larger, faster growing fish of the younger age groups. The higher calculated lengths of these selected fish may account for much of the disagreement in calculated lengths for the first few years. Again, these gangs of nets that had meshes only between 2 and 3 inches possibly took the smaller fish of the older age groups. The selection may explain their slow calculated growth during their early years of life.

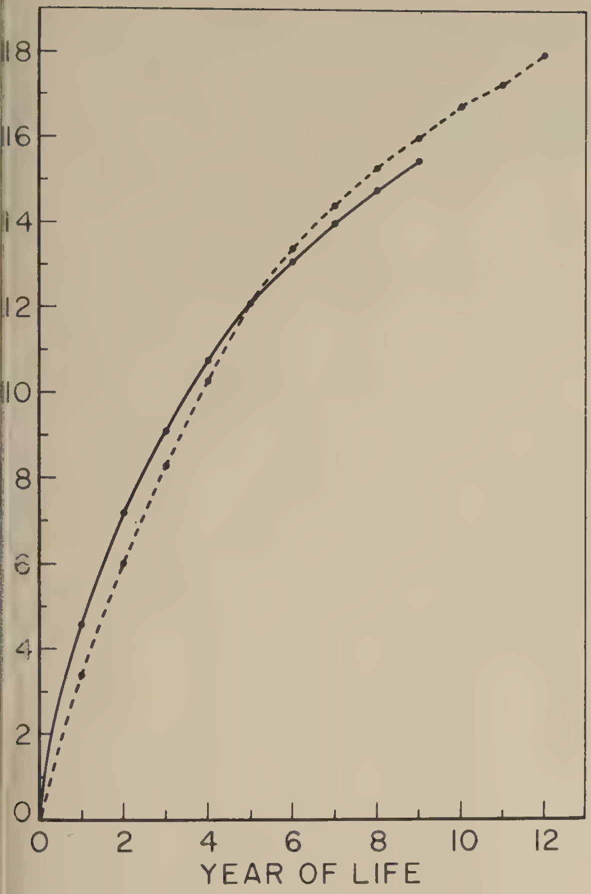
The selective destruction of the faster growing fish in the fishery probably contributed little, if at all, to the systematic discrepancies in calculated length of round whitefish at either the Apostle Islands or Isle Royale. Commercial exploitation of the species in Lake Superior (see Introduction) is extremely limited.

Higher natural mortality rate among fast growing fish than among slow growing was demonstrated by Hile (1936) in the cisco population of Silver Lake, Wis., but he found no evidence of similar mortality in three other cisco stocks. The possibility that differential natural mortality accounted for some of the discrepancies in the calculated growth of round whitefish does exist, but materials for verifying or disproving this possibility are not available.

The estimates of the general growth in length have been based on all age groups because of insufficient evidence of bias to exclude any one of them. Although some younger age groups may give overestimates of calculated growth, due to gear selection, their inclusion tends to compensate any underestimates from the older age groups, which, too, may have suffered gear selection or may have lost their faster growing members either to the fishery or through higher natural mortality.

Two basically valid approaches to the estimation of general growth are given—the grand average calculated lengths and the summation of the grand average annual increments of length (bottom sections, tables 7 and 8). Apostle Islands round whitefish gave closely similar results by both methods, but at Isle Royale the sums of the increments yielded the higher calculated lengths in the later years of life. The summation of increments has been used for the preparation of table 9 and figure 4 since it avoids the irregularities caused by successive dropping out of age groups.

The trends in growth of round whitefish were noticeably different in the Apostle Islands and at Isle Royale. The calculated length at the end of the first year at Isle Royale (3.4 inches) was 1.2 inches shorter than that of round whitefish from the Apostle Islands (4.6 inches). The second-



URE 4.—Calculated growth in length of round whitefish
rom the Apostle Islands (solid line) and Isle Royale
broken line).

r increment was the same in both populations
6 inches), but in the third through eighth years,
e Royale fish grew the faster. (The increments
re the same in the ninth year.) The two popu-
ions had the same calculated length (12.1
hes) by the end of the fifth year, but thereafter
e Royale fish were the longer each year through
ninth where further comparisons became im-
ssible. The major difference between the two
cks, then, was the more rapid growth in the
ostle Islands in the first year and equal or
ter growth at Isle Royale from the second
ough the ninth years of life.

TABLE 9.—*Calculated growth in length of round whitefish from the Apostle Islands and at Isle Royale as estimated from the data for the combined age groups*

[Based on summation of grand average annual increments; data from bottom of tables 7 and 8]

Year of life	Apostle Islands		Isle Royale	
	Length (inches)	Increment	Length (inches)	Increment
1	4.6	4.6	3.4	3.4
2	7.2	2.6	6.0	2.6
3	9.1	1.9	8.3	2.3
4	10.8	1.7	10.3	2.0
5	12.1	1.3	12.1	1.8
6	13.1	1.0	13.4	1.3
7	14.0	0.9	14.4	1.0
8	14.8	0.8	15.3	0.9
9	15.5	0.7	16.0	0.7
10	---------	---------	16.8	0.8
11	---------	---------	17.3	0.5
12	---------	---------	18.0	0.7

t is conceivable that the differences in growth
e of round whitefish of the Apostle Islands and
e Royale, may not be exactly as indicated in
le 9. An accurate body-scale relation could
be determined at Isle Royale because no small
were captured. In consequence, lengths of
e Royale fish were computed from the body-scale relation determined for round whitefish of the Apostle Islands. Should the body-scale relation actually differ materially between the two stocks apparent differences in growth rate would appear even though the true differences were small.

Both stocks of round whitefish made their best growth in length in the first year of life; thereafter the annual increments decreased with few exceptions. The increments beyond the second year were low, and beyond the sixth year were 1 inch or less.

At the present time there is no legal commercial size limit on the round whitefish in any of the Great Lakes. The only factor governing sale is acceptability on the commercial market. Prospects for increased exploitation are dimmed by the fact that nearly or fully 7 years are required for the species to reach a practical commercial size of about 14 inches.

GROWTH IN WEIGHT

Calculated growth in weight of round whitefish from the Apostle Islands and Isle Royale (table 10) was determined by applying calculated lengths (sum of the average increments) of table 9 to the length-weight equation given earlier. The estimates of growth in weight at Isle Royale are subject to possible error since calculated weights were computed from the length-weight equation derived for the Apostle Islands stock. As was explained in the section on the length-weight relation, however, the equation based on Apostle Islands fish, caught in various months, may be more satisfactory for the Isle Royale stock than one based on limited collections made in a single month in the latter area. In the Apostle Islands the annual increments of calculated weight increased from 0.4 ounce in the first year to 2.5 ounces in the fifth year of life. The weight increments for subsequent years all fell within the range of 2.2 to 2.5 ounces. At Isle Royale yearly weight increments increased progressively from 0.1 ounce in the first year to 3.2 ounces in the fifth year of life. Thereafter the increments fluctuated without trend but all fell within the range of 2.2 to 3.4 ounces. Annual increments of weight for Isle Royale round whitefish were significantly higher than those of the Apostle Islands from the fifth year through the ninth year of life (fig. 5). Conversely, Apostle Islands fish revealed better weight increments in the first 3 years. Relatively slow growth in weight is evident in both populations. Nearly 7 years are required to reach a weight of ¾ pound.

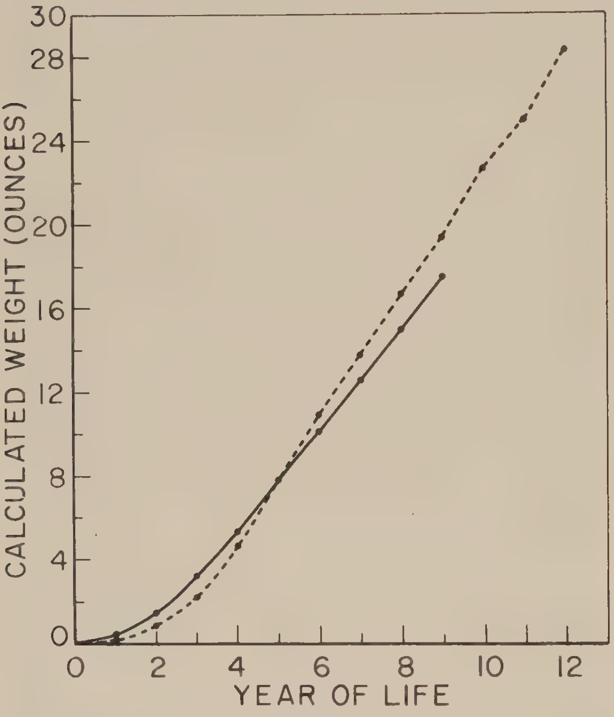


Figure 5.—Calculated growth in weight of round whitefish from the Apostle Islands (solid line) and at Isle Royale (broken line).

Table 10.—*Calculated growth in weight of round whitefish from the Apostle Islands and at Isle Royale*

[Weights were computed from the general length-weight relation and correspond to the lengths in table 9]

Year of life	Apostle Islands		Isle Royale	
	Weight (ounces)	Increment	Weight (ounces)	Increment
1	0.4	0.4	0.1	0.1
2	1.5	1.1	0.8	0.7
3	3.1	1.6	2.3	1.5
4	5.4	2.3	4.7	2.4
5	7.9	2.5	7.9	3.2
6	10.1	2.2	10.9	3.0
7	12.6	2.5	13.8	2.9
8	15.0	2.4	16.7	2.9
9	17.4	2.4	19.3	2.6
10	-----	-----	22.6	3.3
11	-----	-----	24.8	2.2
12	-----	-----	28.2	3.4

SIZE AND AGE AT MATURITY
SEX RATIO

No collections made near or during the spawning runs were included in determining the size and age at maturity or sex ratios of round whitefish from the Apostle Islands since segregation by sex and maturity can bias samples obtained at this period.

The shortest mature males were 7.0–7.4 inches long (table 11) and 100-percent maturity was reached at 13.0–13.4 inches. This range of 6 inches seems to be large, particularly for a species of relatively slow growth. One immature male was found at 14.0–14.4 inches, but it is highly probable that the gonads of this fish were undeveloped for other physiological reasons. The shortest mature female was at 6.5–6.9 inches. The suspicion that the single mature specimen at this length may be exceptional is supported by the fact that the next mature female was found at 8.5–8.9 inches. By the 10.0- to 10.4-inch interval, 60 percent of the females were mature, and all were mature at 12.5 inches. Male round whitefish apparently mature at a slightly smaller size than females, but 100-percent maturity is reached by both sexes at about the same length.

The youngest mature fish of both sexes belonged to age-group II (table 12). The single mature female in this age group, however, was the same fish found at 6.5–6.9 inches (see table 11). All males were mature at age-group V (one was immature in the VII group) and all females at age-group VI. In the younger age groups the higher percentage of maturity for males than for females is in agreement with findings for other species.

A commercial fishery for the round whitefish in the Apostle Islands region, based on the acceptable minimum length of about 14 inches (age-group VII), would take few, if any, immature fish.

Male round whitefish outnumbered females in e Apostle Islands (table 13) in the younger age oup. The ratio was near 50–50 in age-groups and V, and females became progressively more ntiful in age-groups VI through IX. Males nstituted only 20 percent of age-group IX.

BLE 11.—*Relation between length and sexual maturity of round whitefish from the Apostle Islands*

ll fish shorter than 6.5 inches were immature; all fish longer than 14.4 inches were mature]

tal length (inches)	Males			Females		
	Number immature	Number mature	Percentage mature	Number immature	Number mature	Percentage mature
.9	11	0	0.0	11	1	8.3
.4	41	4	8.9	14	0	0.0
.9	9	2	18.2	15	0	0.0
.4	10	2	16.7	10	0	0.0
.9	21	1	4.5	18	1	5.3
.4	21	1	4.5	22	1	4.3
.9	11	4	26.7	14	5	26.3
10.4	5	11	68.8	10	15	60.0
10.9	9	28	75.7	4	17	81.0
11.4	6	22	78.6	4	22	84.6
11.9	2	31	93.9	8	32	80.0
12.4	1	30	96.8	3	22	88.0
12.9	1	32	97.0	0	49	100.0
13.4	0	28	100.0	0	28	100.0
13.9	0	24	100.0	0	25	100.0
14.4	1	23	95.8	0	21	100.0

BLE 12.—*Relation between age and sexual maturity of round whitefish from the Apostle Islands*

fish younger than age-group II were immature; all fish older than age-group VII were mature]

ge group	Males			Females		
	Number immature	Number mature	Percentage mature	Number immature	Number mature	Percentage immature
	72	9	11.1	65	1	1.5
	66	23	25.8	61	13	17.6
	10	78	88.6	6	107	94.7
	0	67	100.0	3	47	94.0
	0	47	100.0	0	54	100.0
	1	26	96.3	0	36	100.0

BLE 13.—*Sex composition of age groups of round whitefish from the Apostle Islands*

[No sex record for 47 fish]

Age group	Number of males	Number of females	Percentage males
	1	1	50.0
	82	66	55.4
	110	78	58.5
	135	134	50.2
	64	66	49.2
	51	58	46.8
	28	37	43.1
	11	16	40.7
	2	8	20.0
Total	484	464	51.1

FECUNDITY

The number of eggs was estimated for 37 round whitefish collected in the Apostle Islands area between September 15 and October 20, 1960. Before estimates of egg numbers were undertaken, a test was made to determine the relative dependability of overnight drying at room temperatures and oven drying as described by Smith (1956).

The testing procedure was first to break up thoroughly the alcohol-preserved ovaries and separate and remove connective tissue and other foreign matter. Eleven random samples of 500 eggs each, all from the same ovary, were dried at room temperature and weighed on a milligram balance. The samples were then further dried in an oven at 60° C. and reweighed. Since further weight loss was found to be nearly constant for all samples after oven drying, this additional step was judged to be unnecessary.

For each of the 37 fish, a random sample of either 500 or 1,000 dried eggs (depending upon the ovary size) was removed from each ovary and weighed. The remainder of the eggs were also weighed and the total number estimated by direct proportion. The accuracy of this method was tested by actually counting the eggs in six ovaries. The errors (all slight overestimates) ranged from 0.02 to 4.9 percent and averaged 1.3 percent.

The average number of eggs for fish grouped by 0.5-inch intervals increased irregularly with increased fish length (table 14 and fig. 6). The single specimen at 10.5–10.9 inches had 1,076 eggs in its ovary, and the fish at 17.0–17.4 inches

TABLE 14.—*Relation between the length of round whitefish from the Apostle Islands and the number of eggs in the ovaries*

Total length (inches)	Number of fish	Number of eggs per fish		Number of eggs per ounce of fish
		Average	Range	
10.5–10.9	1	1,076		199
11.5–11.9	1	2,688		395
12.0–12.4	3	2,461	1,906– 3,022	300
12.5–12.9	4	2,970	2,211– 4,595	323
13.5–13.9	3	3,623	2,986– 3,951	335
14.0–14.4	2	3,947	3,656– 4,237	290
14.5–14.9	4	4,458	3,381– 5,170	312
15.0–15.4	8	5,438	4,014– 6,601	340
15.5–15.9	2	7,086	6,920– 7,251	369
16.0–16.4	5	7,673	6,020– 9,254	364
16.5–16.9	3	10,459	8,053–11,888	436
17.0–17.4	1	10,187		398
All lengths	37	5,330	1,076–11,888	341

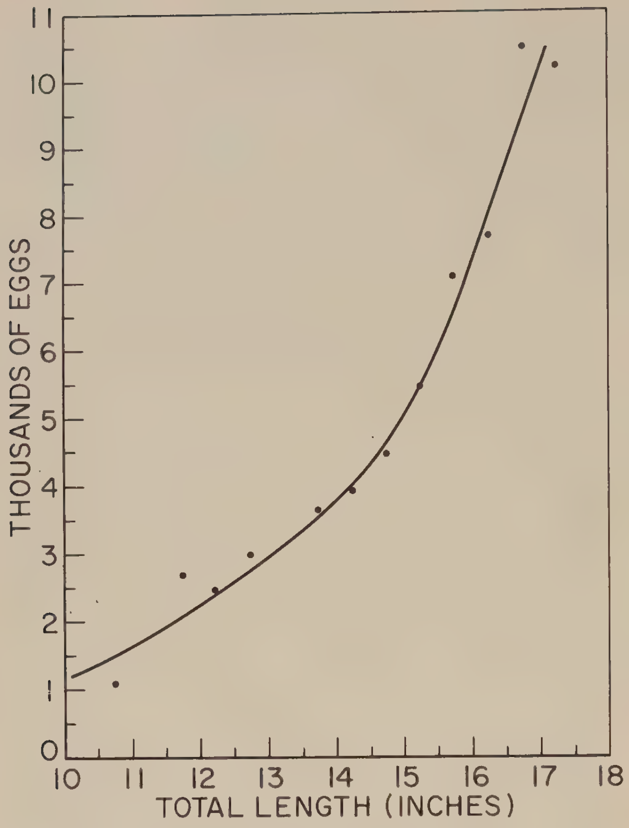


FIGURE 6.—Relation between length of round whitefish from the Apostle Islands and number of eggs per ovary. The dots represent the empirical data for 0.5-inch length groups; the curve was sketched by inspection.

contained 10,187 eggs. The mean number of eggs for all fish was 5,330.

The number of eggs per ounce of fish varied irregularly with length but tended to be higher among the longer than among the shorter fish. The number per ounce was low for the single female at 10.5–10.9 inches (199). The highest number (436) was for fish 16.5–16.9 inches long. The mean number of eggs per ounce of fish for all individuals was 341.

Only one publication could be located that included egg counts for round whitefish. Brice (1898) listed an average of 3,500 eggs per female; a 1.75-pound female produced 12,000 eggs.

SUMMARY

1. The round whitefish is found in all the Great Lakes but Lake Erie. It occurs northward to the Arctic and is common in the streams and lakes of eastern Canada and in the St. Lawrence River and Hudson River drainages.

2. The investigation of round whitefish from Lake Superior was based on data from 1,173 specimens collected in the Apostle Islands area and 103 captured at Isle Royale. This study is the first on the age and growth of the species in the Great Lakes.

3. Round whitefish production for the U.S. waters of Lake Superior generally has been small and averaged only 26,600 pounds in 1929–59. Canadian (Ontario) production averaged 11,000 pounds in 1952–59.

4. Slight year-to-year differences in time of annulus formation were found at both the Apostle Islands and Isle Royale. The period of annulus formation for the Apostle Islands stock appears to fall mostly in June, but 1960 Isle Royale samples suggest a later annulus formation date at this location.

5. The average age of 6.0 years at Isle Royale was concluded to be significantly higher than the mean of 4.2 years in the Apostle Islands. Age-group IV was dominant at both localities and the oldest fish taken belonged to age-group IX in the Apostle Islands and to age-group XII at Isle Royale.

6. Length distributions of the well-represented age groups demonstrate a fairly large range in length at both the Apostle Islands and Isle Royale. The distributions of I- and II-group round whitefish from the Apostle Islands did not overlap, but those of other successive age groups overlapped from 2 to 4 inches.

7. The general length-weight relation of round whitefish from the Apostle Islands is described by the equation: $\log W = -3.40468 + 3.2231 \log L$, where W is weight in ounces, and L is total length in inches. Weight varied according to state of maturity and date of capture. The length-weight equation derived for Apostle Islands fish was accepted for the Isle Royale stock since a comparison of empirical weights of fish captured in August from both areas revealed little difference.

8. The relation between the total body length in inches (L) and the magnified (×43) scale diameter in millimeters (S) is described by the equation, $L = 1.1049 + 0.050\ S$. The intercept was taken to be 1.1 inches on the length axis and lengths at formation of each annulus were calculated nomographically.

9. The different age groups of both the Apostle Islands and Isle Royale stocks exhibited systematic discrepancies in the form of a progressive

rease of calculated lengths with increase in the of the fish on which calculations were based.

0. The most likely contributing factors for the tematic discrepancies are: biased samples from r selection; selective destruction of the faster wing fish in the fishery; higher natural mortal- for fish with rapid growth than for those with v growth.

1. First-year growth in length in the Apostle ınds (4.6 inches) was greater than at Isle Royale 4 inches), but in subsequent years of life growth Isle Royale exceeded or equaled that in the ostle Islands. The Apostle Islands fish had the ater calculated lengths (by 1.2 to 0.5 inches) ough the first 4 years, the lengths for the two cks were equal at 12.1 inches in 5 years, and the Royale fish were the longer (by 0.3 to 0.5) in years 6–9. Both stocks required nearly fully 7 years to reach an acceptable market gth of 14 inches.

2. Differences between the two stocks in wth in weight resembled those of growth in gth. Both required nearly 7 years to reach ee-quarters of a pound.

3. The slow growth of round whitefish from the ostle Islands and at Isle Royale suggests that sibilities for greatly increased commercial loitation are small.

4. The percentage of maturity of male round tefish from the Apostle Islands was higher than t of females at the shorter lengths and younger s but 100-percent maturity was reached by h sexes at about the same length and age. All shorter than 6.5 inches were immature and all ger than 14.4 inches were mature. Youngest nature fish of both sexes belonged to age-group Only one male (possibly aberrant) older than IV group and no females older than the V up were immature.

5. Male round whitefish from the Apostle nds outnumbered females in the younger age ups (II and III) but females became progres- lly more plentiful as age increased and domi- ed the higher ages.

6. Estimates of the number of eggs in 37 nd whitefish ovaries ranged from 1,076 to 87 and averaged 5,330 eggs for fish 10.5–17.4 es long. The average numbers of eggs for fish uped by 0.5-inch intervals increased irregularly ıncreased fish length. The mean number of per ounce of fish was 341.

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AGE AND GROWTH OF THE WHITEFISH IN LAKE SUPERIOR

By William R. Dryer, *Fishery Biologist*
Bureau of Commercial Fisheries

ABSTRACT

he average annual commercial production of white- in the U.S. waters of Lake Superior dropped from 4,000 pounds in 1879–1908 to 504,000 pounds in –59. The modern production, though far below the lier, has accounted for more than 10 percent of the al value of the fishery in all but one of the last 20 rs.

ata are given on growth rate, age and year-class nposition, size distribution, and length-weight tion of 1,800 fish collected in 1957–59 at Bayfield, ., and Marquette, Whitefish Point, and Dollar tlement, Mich. Studies of the body-scale relation, ratio, and age and size at maturity were limited to collected at Bayfield.

he age composition and mean age varied widely by and year of capture. Oldest fish were those of the Bayfield samples which were dominated by age- up VII and averaged 5.5 years old. The youngest e from Whitefish Point in 1959; age-group III was ninant, and the mean age was 3.2 years. The lence on the strength of year classes was not clear- but it was obvious that fluctuations in stocks of erent areas were largely independent.

he percentage of legal-size fish (17 inches or longer) ge groups ranged widely; only 8.6 percent of the V group were legal in the 1957 Bayfield collections, whereas 100 percent of fish of the same age were legal in the 1957–59 collections from Whitefish Point. The weight of whitefish in the combined samples increased as the 3.2408 power of the length.

The growth rate from the fastest to the slowest growing stocks ranked as follows: Whitefish Point; Dollar Settlement and Marquette (fish from the two ports reversed ranks after 3 years); Bayfield. The major differences in growth in length among the various stocks occurred during the first years of life. Beyond the fifth year the annual increments were nearly the same in all stocks. The whitefish from Whitefish Point, Dollar Settlement, and Marquette are among the fastest growing in the Great Lakes.

The differences among the Lake Superior stocks in age and year-class composition, and in growth rate offer convincing evidence that populations of different areas are entirely independent.

The sexes were almost equally represented (51.5 percent males) in the combined Bayfield samples, but males were scarce in age groups older than VIII. Whitefish from Bayfield shorter than 14.5 inches were immature and those larger than 17.4 inches were mature. The youngest mature fish belonged to age-group V, and all older than the VII group were mature.

he whitefish, *Coregonus clupeaformis* (Mitch- , is the largest and the most widely known core- ine in the Great Lakes; it occurs in all five es. It was the principal species sought in the ly Great Lakes fisheries: for the period 1941–54, whitefish comprised more than 10 percent of the total value of the U.S. catch in the Great Lakes (only exception in 1943 when the value was 9 percent); for the years 1947–50 it ranked first in money value among all Great Lakes species. The 1948 production of whitefish in U.S. waters amounted to 12¼ million pounds, with a value of 3¾ million dollars, which represents 30 percent of the total value of the Great Lakes catch.

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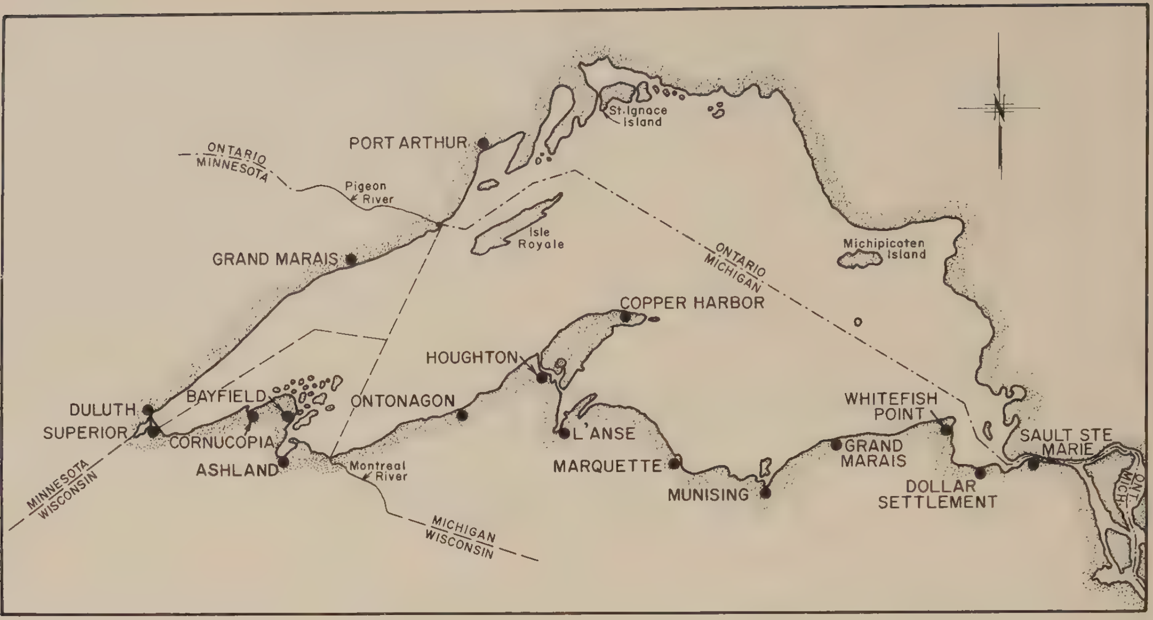
ONTARIO
MINNESOTA
PORT ARTHUR
Pigeon River
St. Ignace Island
Isle Royale
GRAND MARAIS
ONTARIO
MICHIGAN
Michipicoten Island
COPPER HARBOR
HOUGHTON
DULUTH
SUPERIOR
BAYFIELD
CORNUCOPIA
ASHLAND
ONTONAGON
Montreal River
L'ANSE
MARQUETTE
MUNISING
WHITEFISH POINT
GRAND MARAIS
DOLLAR SETTLEMENT
SAULT STE MARIE
MINNESOTA
WISCONSIN
MICHIGAN
WISCONSIN

Figure 1.—Map of Lake Superior.

The recent production of whitefish in Lake Superior, though far below that of the earlier years, still has been of great economic importance. The species has accounted for more than 10 percent of the total value of the U.S. catch in this lake for the period 1941–59 (exception in 1952 when the whitefish accounted for only 7 percent), and the production in 1956 represented over 26 percent of the value of the U.S. catch. The progressive decline of the lake trout (*Salvelinus namaycush*) makes the high-priced whitefish relatively even more valuable, and greater exploitation of it is to be expected to supplement income from the lower-priced lake herring (*Coregonus artedii*) and chubs (*Coregonus* spp.). Sound management and rational exploitation require knowledge of the species, such as average size composition, growth rate, and maturity. The present paper is a contribution to that knowledge.

Relatively little is known of the whitefish in Lake Superior. The only published study on growth is that of Edsall (1960) on the unexploited stock of dwarf whitefish in Munising Bay.

MATERIALS AND METHODS

The present study is based on 1,800 whitefish captured off four Lake Superior ports (fig. 1) from 1957 through 1959. The number of fish collected at each port (table 1) was: Bayfield, 748; Marquette, 458; Whitefish Point, 340; Dollar Settlement, 254.

More than one-half of the whitefish taken at Bayfield were from commercial pound nets. Most pound nets at Bayfield are 50 to 70 feet deep and have a 4¾-inch-mesh pot. The whitefish collections from the other ports were all from commercial trap nets with a 4½-inch-mesh pot. Net-run samples were taken from commercial pound nets and trap nets by dipping out 150–200 fish without regard to size. When the total number was less than 150–200 fish, the sample included the entire catch.

The remainder of the Bayfield samples came from commercial gill nets of 4½-inch mesh and from experimental gill nets and trawls fished from the Bureau's research vessel *Siscowet*.

All of the fish listed for the *Siscowet* at Bayfield were used in some phase of this study, but they were not employed as part of the materials on age composition and growth since they are not comparable to samples from commercial gear. The small individuals taken with trawls were of particular value in studies of the body-scale regression and length-weight relation. Helpful also were records of calculated lengths that illustrated the effects of gear selection of commercial nets.

The listings in table 1 exclude individuals not used in age and growth analyses because of scale ʟᴇ 1.—*Locality, gear, and date of capture of Lake perior whitefish used for the study of age and growth*

Port	Date	Number of fish, by gear				Total
		Trap net[2]	Pound net[2]	Gill nets[1]	*Siscowet* experimental gear[3]	
	1957					
ld, Wis.	June 13	------	135	------	----------	135
	July 22	------	138	------	----------	138
	Aug. 15	------	99	------	----------	99
ıette, Mich.	June 20	20	--------	------	----------	20
	July 16	51	--------	------	----------	51
	Sept. 30	117	--------	------	----------	117
ish Point, Mich.	June 19	123	--------	------	----------	123
	Sept. 20	61	--------	------	----------	61
Settlement, n.	July 24	96	--------	------	----------	96
	Aug. 13	24	--------	------	----------	24
	1958					
ld, Wis.	June–Nov.	------	--------	------	93	93
ette, Mich.	Oct. 2	141	--------	------	----------	141
ish Point, Mich.	Sept. 30	108	--------	------	----------	108
	1959					
ld, Wis.	June–Nov.	------	--------	------	138	138
	June 1	------	106	------	----------	106
	Dec. 18	------	--------	39	----------	39
ette, Mich.	Sept. 28	129	--------	------	----------	129
ish Point, Mich.	Sept. 24	48	--------	------	----------	48
Settlement, n.	Sept. 24	134	--------	------	----------	134
	1957–59					
ld, Wis.	All months	------	478	39	231	748
ette, Mich.	do	458	--------	------	----------	458
ish Point, Mich.	do	340	--------	------	----------	340
Settlement, a.	do	254	--------	------	----------	254
	1957					
ts	All months	492	372	------	----------	864
	1958					
	do	249	--------	------	93	342
	1959					
	do	311	106	39	138	594
Grand total		1,052	478	39	231	1,800

inch mesh.
inch mesh.
nets 1- to 5-inch mesh by ½-inch intervals and 31-foot semiballoon

neration or extreme difficulty in identifying uli. The number of fish excluded from the sample was less than 2 percent.

otal lengths (from the tip of the head to the f the tail, with the lobes compressed to give maximum measurement) were read from a suring board calibrated in 0.1-inch intervals. ghts were determined with a spring balance were recorded either to the nearest 0.1 ounce 1 pound. All weights given in this paper are unds.

ne sex and state of gonads were determined sh from all the *Siscowet* collections and about ercent of the Bayfield pound net collections. remaining 25 percent of the Bayfield pound collections were omitted from the sex-ratio and rity studies because of uncertainty as to the Most of these fish were from a single sample collected in June 1957. Data on sex and state of gonads are lacking for samples from commercial gill nets at Bayfield and for collections from all the other ports. The whitefish captured at Marquette, Whitefish Point, and Dollar Settlement were marketed in the round and hence could not be opened. The fish from the commercial gill nets at Bayfield had been dressed before they were examined. A whitefish was considered mature if it would have spawned in the fall of the year of capture.

Scales were removed from the left side of the fish at a point midway between the lateral line and the middle of the base of the dorsal fin.

Scale impressions were made in cellulose acetate (Smith, 1954) and were magnified 42 diameters by means of a microprojector (Moffett, 1952). Diameters of scales and of growth fields within scales were measured through the focus along a line that roughly bisected the anterior field and were recorded to the nearest millimeter.

Age groups are designated by Roman numerals corresponding to the number of completed annuli. All the fish were considered to have passed into the next higher age group on January 1. A virtual annulus was credited, therefore, at the edge of the scale on all fish collected between January 1 and the time an annulus was actually completed.

Among the whitefish collected during the period of annulus formation in mid-June, no difficulties were experienced in separating individuals with a new annulus from those in which the year-mark had not yet been completed. Most of the scale samples were collected before or well after growth had started; for them the interpretation of marginal growth outside the last visible annulus obviously offered no problem.

Statistics on commercial production were obtained from various sources as given in the next section.

PRODUCTION OF WHITEFISH IN LAKE SUPERIOR

The Lake Superior fisheries were the last to be developed in the Great Lakes. As in the other Great Lakes, the whitefish was the principal species sought in the early years of fishing. Seines were the first gear fished along the south shore of Lake Superior, but because of the rough, rocky bottom their usefulness was limited. Gill nets were soon employed; and the pound net, introduced in this country from Scotland in 1836, was established in Whitefish Bay about 1860. The pound net was first fished in the Apostle Islands area in 1871, and by 1885 about 125 were in use. Only 40 pound nets were fished in the Apostle Islands in 1960. The trap net, which was invented by Lake Ontario fishermen in 1865, was introduced in Lake Superior during the early 1900's. This net was not adapted for taking whitefish until the 1930's and since then has been important only in Michigan. The use of trap nets is prohibited in Wisconsin and Minnesota waters. The first steamer was introduced in 1871, and the first motor boat appeared at Marquette, Mich., in 1899.

Up to 1890 whitefish were the principal species in the commercial production in United States waters of Lake Superior (Koelz, 1926). Between 1891 and 1899 the lake trout occupied first place, and in the early 1900's large-scale production of lake herring placed them in first rank. The whitefish has held third position behind the lake herring and lake trout up to the recent collapse of the lake trout fishery.

The statistical records of whitefish production in Lake Superior (table 2) came from various sources. The figures through 1940 are from Gallagher and Van Oosten (1943). The U.S. data for 1941–59 are from Lake Fisheries issued by the Bureau of Commercial Fisheries. The later records for Ontario were issued by the Province.

The first published record of whitefish production in Lake Superior is for 1867 in Ontario. The first record of whitefish production in the U.S. waters of Lake Superior is for 1879 (fig. 2).

The catch of whitefish in U.S. Waters of Lake Superior was 2¼ million pounds in 1879 and exceeded 4½ million pounds in 1885—the highest production recorded. Landings fell off drastically during the following 30 years, and by 1913 the catch reached an all-time low of 113,000 pounds.

Koelz (1926) stated pessimistically that from a commercial point of view the whitefish was practically extinct along the United States shore of Lake Superior in 1922 when the total catch in U.S. waters was 319,000 pounds. The production of 144,000 pounds in 1923 marked a still further decline. It was not until the early 1930's that whitefish production in U.S. waters began to improve. An erratic increase in the catch continued for about 20 years, and in 1949 the take reached 1,284,000 pounds, the highest since 1903. Since 1949 the catch of whitefish in U.S. waters has fluctuated widely between 1,040,000 pounds in 1950 and 309,000 in 1958. The 1911–59 average production of 508,000 pounds was only 23.2 percent of the 1879–1908 mean of 2,194,000.

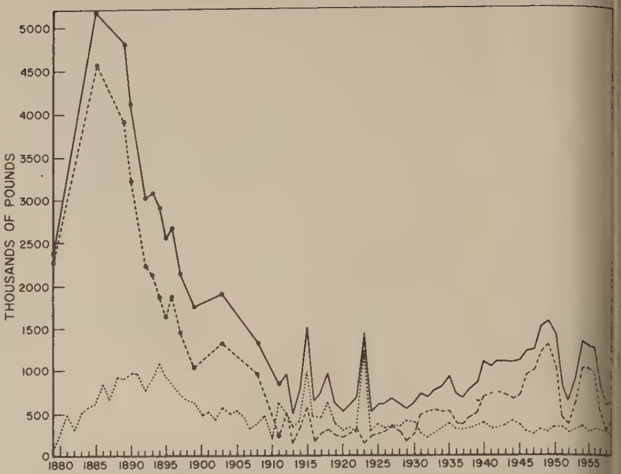

FIGURE 2.—Production of whitefish in Lake Superior, 1879–1959. United States, short dashes; Ontario, dotted lines; entire lake, solid line. Because of the numerous interruptions in the records for U.S. waters, the points for individual years prior to 1912 are shown by dots on the lines for the catch in U.S. waters and in the entire lake.

The distribution of the yield of whitefish from the different States has not changed greatly during the period for which statistics are available. With the exception of 10 years when Wisconsin had the largest catch (1885, 1925, 1946–50, and 1955–57) Michigan has dominated the yield of whitefish (table 3). For the period 1885–1908 Michigan contributed 70.3 percent of the total U.S. production, Wisconsin 23.8 percent, and Minnesota 5.9 percent. In 1911–59 Michigan continued to occupy first place but with a slightly lower percentage (62.8 percent). Wisconsin's contribution increased to 35.9 percent, and Minnesota's dropped from 5.9 to 1.3 percent.

The production of whitefish in Canadian waters of Lake Superior has not shown the wide fluctuations experienced in U.S. waters. Production exceeded 1,000,000 pounds only in 1894 (1,056,000 pounds) and in 1923 (1,268,000 pounds[1]). On-

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[1] A possibility exists that the 1923 statistic may be erroneous. The figure 268,000 pounds would be in better agreement with the production from Ontario in neighboring years. There are no records, however, from which to check this figure.

2.—*Production (thousands of pounds) of whitefish in Lake Superior, 1879–1959*

are given for U.S. waters in all years with records for both Wisconsin and Michigan]

Year	United States				Canada	Grand total
	Minnesota	Wisconsin	Michigan	U.S. total	Ontario	
	--------	--------	--------	2,257	99	2,356
	--------	--------	--------	--------	245	--------
	--------	--------	--------	--------	466	--------
	--------	--------	--------	--------	320	--------
	--------	--------	--------	--------	509	--------
	--------	--------	--------	--------	565	--------
	628	2,243	1,701	4,572	606	5,178
	--------	--------	--------	--------	847	--------
	--------	--------	--------	--------	657	--------
	--------	--------	--------	--------	932	--------
	211	951	2,736	3,899	896	4,795
	40	1,109	2,064	3,213	978	4,192
	--------	--------	3,848	--------	967	--------
	--------	206	2,015	2,221	784	3,004
	--------	251	1,919	2,170	899	3,068
	--------	301	1,554	1,855	1,056	2,911
	--------	301	1,325	1,626	911	2,538
	--------	700	1,162	1,862	796	2,658
	31	162	1,246	1,438	686	2,124
	--------	--------	1,088	--------	659	--------
	13	62	1,058	1,132	623	1,756
	--------	--------	829	--------	462	--------
	--------	--------	794	--------	483	--------
	--------	--------	1,513	--------	417	--------
	8	129	1,200	1,336	564	1,900
	--------	--------	630	--------	478	--------
	--------	--------	684	--------	524	--------
	--------	--------	587	--------	452	--------
	7	--------	576	--------	301	--------
	4	174	764	942	363	1,305
	--------	24	--------	--------	470	--------
	--------	9	--------	--------	202	--------
	--------	13	202	214	620	834
	--------	32	456	488	459	947
	(1)	20	93	113	357	470
	1	18	335	355	397	752
	2	43	522	567	955	1,522
	1	44	131	175	462	637
	1	36	220	257	452	708
	3	66	258	327	628	955
	4	62	174	240	366	606
	7	16	198	221	303	524
	8	56	192	255	329	585
	7	52	260	319	287	606
	5	60	79	144	1,268	1,412
	5	89	142	236	283	519
	5	143	99	247	347	594
	4	90	185	280	317	597
	5	74	249	328	337	665
	3	54	229	286	327	613
	3	62	101	166	389	555
	5	85	161	252	372	623
	12	52	410	474	256	730
	11	57	417	484	193	678
	6	72	442	520	245	765
	10	91	388	488	295	784
	11	73	429	512	377	890
	7	137	230	374	320	694
	7	99	258	364	301	665
	6	123	327	455	312	767
	6	106	385	497	340	837
	9	152	532	692	385	1,077
	9	273	446	728	315	1,042
	9	253	489	751	320	1,071
	5	265	461	732	336	1,068
	15	263	386	663	403	1,066
	11	338	368	717	359	1,076
	13	481	421	915	275	1,190
	11	619	321	951	246	1,197
	11	713	477	1,201	306	1,506
	13	767	504	1,284	277	1,561
	9	523	508	1,040	341	1,381
	14	183	244	442	341	782
	13	140	198	351	268	618
	5	171	431	607	282	889
	8	332	665	1,005	328	1,333
	2	501	497	1,000	254	1,255
	3	544	374	921	303	1,223
	(1)	288	236	525	285	809
	(1)	88	221	309	287	596
	1	121	260	383	210	593

n 500 pounds.

TABLE 3.—*Average annual production (pounds) of whitefish in different States and percentage contribution of each State to the total U.S. catch in Lake Superior in 1885–1908 and 1911–59*

Period and item	Minnesota	Wisconsin	Michigan	Total [1]
1885–1908:				
Average production	117,695	472,899	1,394,964	1,985,558
Percentage	5.9	23.8	70.3	----------
Number of years of record	8	14	21	----------
1911–59:				
Average production	6,510	182,449	318,591	507,550
Percentage	1.3	35.9	62.8	----------
Number of years of record	47	49	49	----------

[1] Sum of the average annual contribution of the States.

tario's average annual production for the period 1879–1908 was 618,000 pounds which was 22.0 percent of the total for Lake Superior. Ontario's average annual production dropped to 368,000 pounds in 1911–59; yet this figure represented 42.0 percent of the mean annual take for the entire lake.

Little or no correlation exists between annual fluctuations in production of whitefish in U.S. and Ontario waters. The lack of correlation suggests that U.S. and Canadian fishermen are exploiting different stocks and that conditions controlling fluctuations of the take are not the same over the entire lake.

AGE AND SIZE AT CAPTURE

AGE AND YEAR-CLASS COMPOSITION

The age and year-class composition of Lake Superior whitefish in net-run samples (table 4) varied considerably from port to port and year to year. Although the data are not sufficient for a dependable ranking, certain year classes clearly were of greater or less than average strength.

The interpretation of data on age composition for judging the strength of year classes can be made uncertain by a variety of disturbing factors. Port-to-port differences or annual fluctuations of cropping rate and differences of natural mortality have a strong influence on the representation of age groups. The age at which a year class appears in the sample also must affect judgment as to the original strength. For example, a year class that makes up 20 percent of the sample as age-group VIII must have been originally much stronger than one that contributes 20 percent as age-group IV.

The 1957 Bayfield samples included 10 age groups (I–X). The percentage representation

TABLE 4.—*Age and year-class composition of whitefish caught in commercial trap nets, pound nets, and gill nets*

[Asterisks indicate dominant year classes in different collections]

Port, year of capture, and item	Age group										Total or average
	I	II	III	IV	V	VI	VII	VIII	IX	X	
Bayfield, 1957:											
Year class	1956	1955	1954	1953	1952	1951	*1950	1949	1948	1947	
Number	2	22	73	6	70	55	81	59	3	1	37
Percentage	0.5	5.9	19.5	1.6	18.8	14.8	21.8	15.9	0.8	0.3	[illegible]
Bayfield, 1959:											
Year class			1956	*1955	1954						
Number			6	117	22						14
Percentage			4.1	80.7	15.2						4.
Marquette, 1957:											
Year class			1954	1953	*1952	1951	1950	1949	1948	1947	
Number			18	63	74	20	7	4	1	1	[illegible]
Percentage			9.1	33.9	39.9	10.7	3.2	2.2	0.5	0.5	[illegible]
Marquette, 1958:											
Year class		1956	*1955	1954	1953	1952	1951	1950		1948	
Number		3	78	29	17	9	3	1		1	14
Percentage		2.1	55.3	20.6	12.1	6.4	2.1	0.7		0.7	3.
Marquette, 1959:											
Year class		1957	1956	*1955	1954	1953	1952			1949	
Number		13	19	61	24	9	2			1	12
Percentage		10.1	14.7	47.3	18.6	7.0	1.6			0.8	4.
Whitefish Point, 1957:											
Year class		1955	*1954	1953	1952	1951	1950				
Number		5	92	61	20	5	1				18
Percentage		2.7	50.0	33.2	10.9	2.7	0.5				3.
Whitefish Point, 1958:											
Year class		1956	*1955	1954	1953	1952					
Number		13	62	21	11	1					10
Percentage		12.0	57.4	19.4	10.2	0.9					3.
Whitefish Point, 1959:											
Year class	1958	1957	*1956	1955		1953	1952				
Number	1	9	24	12		1	1				4
Percentage	2.1	18.8	50.0	25.0		2.1	2.1				3.
Dollar Settlement, 1957:											
Year class			1954	1953	*1952	1951	1950	1949		1947	
Number			14	38	54	9	3	1		1	12
Percentage			11.4	31.7	45.0	7.5	2.5	0.8		0.8	4.
Dollar Settlement, 1959:											
Year class	1958	1957	*1956	1955	1954	1953	1952				
Number	1	40	81	9	1	1	1				13
Percentage	0.7	29.9	60.4	7.3	0.7	0.7	0.7				2.

[1] Average number of annuli.

was 14.8 percent or higher for age-groups III and V–VIII. The high representation (21.8 percent) of age-group VII and the substantial representation of age-group VIII (15.9 percent) indicate that the 1950 and the 1949 year classes were originally strong. The 1953 year class, represented as age-group IV, was obviously weak since it contributed only 1.6 percent to the catch. The average age of 5.5 for the 1957 Bayfield fish was the highest at any port in any year.

Only three age groups (III–V) were represented in the 1959 samples from Bayfield. The 1955 year class as age-group IV was overwhelmingly dominant (80.7 percent). The absence of age groups above V is difficult to explain. The strong 1949 and 1950 year class probably had largely disappeared by reason of advanced age and continued exposure to exploitation, but some representation of the moderately good 1951 and 1952 year classes (age-groups V and VI in 1957; VII and VIII in 1959) should have been expected. The mean age of 4.1 for the whitefish in the 1959 Bayfield samples was 1.4 years younger than that of the 1957 collections.

The age composition of the Marquette samples also varied with year of collection. The 195 year class as age-group V was dominant (39. percent) in 1957 but failed to show strength in 1958 and 1959. The clear dominance of the 195 year class as age-group III in 1958 (55.3 percent and as age-group IV in 1959 (47.3 percent) gives good evidence of strength. The 1954 class, in contrast, was moderately weak. Even though it contributed 20.6 percent to the catch in 1958 its percentage representation was the lowest recorded for both age-groups III and IV and the next t lowest as age-group V. The average ages of th Marquette samples were 4.8 in 1957, 3.8 in 195 (this low value reflected the strong 1955 year class as age-group III), and 4.1 in 1959 (also dominated by the 1955 year class).

The Whitefish Point collections were unique in that they were persistently dominated by age-group III (50.0 to 57.4 percent) in each year This situation well may be the result of small ations in year-class strength and a high ality rate due to the intensive trap net fishery e area. Most of the whitefish at Whitefish t attain legal size during their fourth year of th (age-group III) and consequently become erable to the fishery. Few individuals may ve to represent the older age groups in sub- ent years. Large percentages of the fish in groups younger than III undoubtedly escape the 4½-inch-mesh trap nets. Because of stent dominance by a single age group, ments of year-class strength at Whitefish t are not considered possible. The mean age e Whitefish Point samples varied little from to year—3.6 in 1957, 3.3 in 1958, and 3.2 in .

e 1952 year class dominated (45.0 percent) rap net samples at Dollar Settlement as age- p V in 1957. No samples were collected in , but in 1959 the 1956 year class dominated gly (60.4 percent) as age-group III. Un- tedly both the 1952 and 1956 year classes strong, but lack of data from 1958 makes ation of relative strength difficult. The 1954 1955 year classes appear to have been weak ollar Settlement. The mean age of the r Settlement whitefish was 4.6 in 1957 and 1959.

tle evidence exists for lakewide similarity of ations of year-class strength. The 1955 class was strong at Bayfield and Marquette but weak at Dollar Settlement. The 1952 year class was strong at Marquette and Dollar Settlement but only moderate at Bayfield. The 1949 and 1950 year classes. which were strong at Bayfield, seemingly were too old to be represented in catches at the other ports. The 1956 year class exhibited strength at Dollar Settlement only. No two ports agreed in the appearance of a weak year class.

LENGTH AND WEIGHT OF THE AGE GROUPS

Comments on the sizes of age groups in samples from commercial gear are kept brief since more discriminating data on growth are offered in later sections. The records of table 5 serve, nevertheless, to establish roughly the differences among the several stocks and provide a general idea of the relation between size and age in catches of commercial gear.

The average lengths and weights of the age groups at capture were determined from the combined samples for each locality with the exception of Bayfield where records for the 1957 and 1959 collections were tabulated separately; the 1958 and 1959 *Siscowet* samples were omitted for reasons made clear in the section on calculated growth. Whitefish collected from the commercial fishery at Bayfield in 1959 showed more rapid growth than those in the 1957 samples. Annual differences at other ports were small and erratically distributed; they can be ascribed to the small numbers of fish

5.—*Total length (inches) and weight (pounds) of the age groups of Lake Superior whitefish and percentage of legal fish (17 inches or longer) in each age group*

[Net-run samples from commercial gear]

Port, year and item	Age group									
	I	II	III	IV	V	VI	VII	VIII	IX	X
l, 1957:										
al length	7.5	11.0	13.3	16.6	15.5	16.7	17.4	17.9	19.7	18.6
ght	0.1	0.4	0.7	1.5	1.2	1.5	1.8	1.9	2.6	2.2
nber of fish	2	22	73	6	70	55	81	59	3	1
entage legal	0.0	0.0	0.0	50.0	8.6	25.5	61.7	83.1	100.0	100.0
, 1959:										
al length	----------	----------	16.4	16.8	17.5	----------	----------	----------	----------	----------
ght	----------	----------	1.4	1.6	1.8	----------	----------	----------	----------	----------
nber of fish	----------	----------	6	117	22	----------	----------	----------	----------	----------
entage legal	----------	----------	33.3	34.2	59.1	----------	----------	----------	----------	----------
te, 1957–59:										
l length	----------	14.7	17.1	19.2	20.7	21.8	23.5	24.8	24.2	26.0
ght	----------	1.0	1.7	2.4	3.0	3.6	4.6	5.5	5.0	6.4
nber of fish	----------	16	115	153	115	38	12	5	1	3
entage legal	----------	6.3	58.3	92.8	99.1	100.0	100.0	100.0	100.0	100.0
h Point, 1957–59:										
l length	10.5	15.1	17.1	18.8	21.7	22.9	21.9	----------	----------	----------
gh	0.4	1.1	1.7	2.3	3.6	4.3	3.7	----------	----------	----------
nber of fish	1	27	178	94	31	7	2	----------	----------	----------
entage legal	0.0	0.0	53.4	86.2	100.0	100.0	100.0	----------	----------	----------
ettlement, 1957, 1959:										
l length	10.8	14.7	16.6	17.3	18.0	19.9	21.2	19.7	----------	26.1
gh	0.4	1.0	1.5	1.7	2.0	2.7	3.3	2.6	----------	6.5
nber of fish	1	40	95	47	55	10	4	1	----------	1
entage legal	0.0	0.0	37.9	48.9	78.2	90.0	100.0	100.0	----------	100.0

in some age groups. The sexes were also combined in these data. Sex differences in the average lengths and weights at capture were not appreciable in samples for which records of sex were available.

Some of the differences in the average lengths and weights of whitefish of the same age groups from different localities were striking. The 1957 Bayfield whitefish were the smallest fish, age for age, of all the collections. The average size of the V-group fish, for example, was 6.2 inches shorter and 2.4 pounds lighter than V-group fish from Whitefish Point. Indeed, the weight of the Whitefish Point fish at this age was 3 times that of Bayfield fish. Age-group VII was the youngest at Bayfield in which the average length exceeded the minimum legal size of 17 inches. The mean weight of the 1957 Bayfield whitefish increased less than one-half pound from their fourth to their eighth growing season (from 1.5 to 1.9 pounds).

The 1959 Bayfield whitefish averaged smaller than whitefish from the other ports, but were larger than those in the 1957 Bayfield collections. The average length of the V-group fish, for example, was 17.5 inches, 0.5 inch above the legal minimum and 2 inches longer than the V group in 1957. The weight advantage of the 1959 V group amounted to 0.6 pound.

The available evidence suggests that a temporary improvement in the growth rate of whitefish accounted for the greater size of the age groups in the 1959 samples. Details are not given here since the materials were not suitable for a thorough study of annual fluctuations of growth. They left little doubt, nevertheless, that growth in 1954–57 was substantially more rapid than in the preceding 5 or 6 years (the growth rate dropped sharply in 1958). Since whitefish normally grow much more rapidly in the early than in the late years of life, the relatively young fish of the 1959 samples were in good position to benefit from the 1954–57 period of heightened growth rate. The whitefish caught in 1957 had also lived during most of the period of exceptional growth, but they were of such advanced age that this improved growth did not add materially to their size.

Differences among the average sizes of the fish from other areas of the lake were small at some ages and substantial at others. Among age groups represented by 16 or more fish at each locality, the differences between the largest and smallest fish increased from 0.4 inch and 0.1 pound in age-group II to 3.7 inches and 1.6 pounds in age-group V. Somewhat puzzling is the consistency with which the age groups in samples from Whitefish Point were larger than those from Dollar Settlement. The two collecting localities are barely 30 miles apart (Whitefish Point is at the northwestern entrance to Whitefish Bay and Dollar Settlement at the southern end). The difference appears almost surely to be real, but the true extent of the separation of the two stocks remains to be learned.

The percentage of legal-size whitefish in the age groups was influenced strongly by differences in the growth of fish taken at the various ports (table 5). Not one whitefish in any sample was legal as age-group I, and only one was legal size as age-group II (a 17.1-inch fish captured at Marquette in 1959). At Bayfield in 1957 the first whitefish reached legal size as age-group IV, and age-group IX was the first in which all of the fish were legal size. In 1959 at Bayfield, 33.3 percent of the III-group fish were legal size and 59.1 percent had reached legal size as age-group V.

Much larger percentages of fish reached legal size in the younger age groups at the ports east of Bayfield. More than 50 percent of the III-group fish were legal size at Marquette and Whitefish Point, and all were legal at age-group V at Whitefish Point and at age-group VI at Marquette. It was not until age-group VII was reached that all the fish were legal size at Dollar Settlement.

LENGTH DISTRIBUTION

Data on the length-frequency distribution of the age groups (tables 6, 7, and 8) provide comparisons by age group between the stocks with the slowest and fastest growth and show the length distributions of the combined age groups for the 1957 and 1959 Bayfield samples and the combined collections at Marquette, Whitefish Point, and Dollar Settlement.

The overlap of length distributions of the age groups is influenced strongly by the rate of growth. The range in length of age groups represented by 20 or more fish in the 1957 Bayfield samples (table 6) was 7.9 inches for all age groups except VII where it was 8.9 inches. This wide range in combination with slow growth caused such extensive overlap as to make length an extremely poor index of age. The length interval of 15.0 to 15.9 inches, for example, was represented by seven age

TABLE 6.—*Length distribution of whitefish taken off Bayfield, 1957*

Total length (inches)	Age group									
	I	II	III	IV	V	VI	VII	VIII	IX	X
	2									
		1								
		2	1							
		9	4							
		9	4							
			17		1					
			21		2	1	1			
			18		19	4	1			
		1	6	2	25	13	5	1		
			2	1	17	23	24	9		
				2	3	7	24	24		
				1	2	5	16	13		1
					1	1	5	9	2	
						1	3	2	1	
							2			
								1		
otal number	2	22	73	6	70	55	81	59	3	1
verage length	7.5	11.0	13.3	16.6	15.5	16,7	17.4	17.9	19.7	18.6

os (II–VIII). The span of ages was six at 16.9 inches and several other 1-inch intervals spans of five age groups. Slow growth and l length ranges also caused the distributions e age groups to lie across the legal size limit inches.

e range in length of the age groups in the -59 Whitefish Point samples (table 7) was also (9.9 inches at age-group IV and 4.9 to 7.9 s in other age groups represented by more 20 fish) but overlapping was reduced by more growth. Because of the good growth and a ity of older fish, overlap did not exceed four groups at any 1-inch interval. The length butions of only three groups (III–V) fell s the minimum legal size of 17 inches.

E 7.—*Length distribution of whitefish taken off Whitefish Point, 1957–1959*

al length (inches)	Age group						
	I	II	III	IV	V	VI	VII
	1						
		1					
		5					
		4	5	2			
		9	25	2			
		8	53	9			
			51	19	1		
			30	20	3		
			7	21	1		
			7	9	5	1	
				8	7	1	1
				2	6		1
				2	4	4	
					4		
						1	
al number	1	27	178	94	31	7	2
rage length	10.5	15.1	17.1	18.8	21.7	22.9	21.9

TABLE 8.—*Length distribution of whitefish caught in commercial pound nets, trap nets, and gill nets*

Total length (inches)	Bayfield		Marquette	Whitefish Point	Dollar Settlement
	1957	1959	1957–59	1957–59	1957, 1959
7.0–7.9	2				
8.0–8.9	1				
9.0–9.9	3				
10.0–10.9	13			1	1
11.0–11.9	13		1		
12.0–12.9	18			1	2
13.0–13.9	25		1	5	5
14.0–14.9	42	3	9	11	24
15.0–15.9	53	23	12	36	65
16.0–16.9	76	64	52	70	40
17.0–17.9	60	36	86	71	59
18.0–18.9	38	11	61	53	31
19.0–19.9	18	5	56	29	11
20.0–20.9	7	3	53	22	5
21.0–21.9	2		53	17	4
22.0–22.9	1		41	9	2
23.0–23.9			14	10	4
24.0–24.9			10	4	
25.0–25.9			4	1	
26.0–26.9			4		1
27.0–27.9			1		
Total number	372	145	458	340	254
Average length	15.8	16.9	19.3	18.0	17.0
Percentage legal	33.9	37.9	83.6	63.5	46.1

e lengths of the 1957 Bayfield samples, age os combined, ranged from 7.0 to 22.9 inches and had a mean of only 15.8 inches (table 8). Only 33.9 percent of the fish were legal size. In contrast, the 1959 Bayfield whitefish had a range of only 6.9 inches, from 14.0 to 20.9 inches. The mean length in 1959 was 16.9 inches, and 37.9 percent of the fish were legal size.

The length distributions of the fish from Marquette, Whitefish Point, and Dollar Settlement were similar. The range from the shortest to the longest fish was 15.9 inches at Whitefish Point and 16.9 inches at Marquette and Dollar Settlement. The average lengths of the whitefish from these ports ranged from 17.0 inches at Dollar Settlement to 19.3 inches at Marquette. The percentage of legal-size fish in the total catches varied considerably—36.1 percent at Dollar Settlement, 63.5 percent at Whitefish Point, and 83.6 percent at Marquette.

LENGTH-WEIGHT RELATION

The general length-weight relation of the Lake Superior whitefish (table 9) was based on the combination of materials regardless of locality, year and season of capture, type of gear, sex, or state of maturity. Undoubtedly the length-weight relation varies during the year and between ripe and recently spent females, as was demonstrated for Lake Erie whitefish by Van Oosten and Hile (1949). The data for this study were not affected by the presence of spawning fish as all fish used were collected in the summer, none later than September 30. Differences among samples from different ports were slight. The lack of small fish from ports east of Bayfield prevented construction of length-weight curves for comparison of localities.

TABLE 9.—*Length-weight relation of Lake Superior whitefish of the combined collections of 1957–59*

Number of fish	Total length [1] (inches)	Weight (pounds)		Number of fish	Total length [1] (inches)	Weight (pounds)	
		Empirical	Calculated			Empirical	Calculated
1	5.9	0.06	0.05	156	17.3	1.69	1.70
20	6.2	0.06	0.06	142	17.8	1.81	1.86
10	6.7	0.06	0.08	118	18.2	2.01	2.02
4	7.1	0.11	0.10	82	18.7	2.21	2.20
2	7.7	0.15	0.12	68	19.2	2.41	2.40
4	8.2	0.13	0.15	52	19.7	2.54	2.61
14	8.7	0.20	0.19	44	20.2	2.80	2.83
19	9.2	0.25	0.22	33	20.7	3.05	3.06
22	9.7	0.26	0.26	28	21.2	3.42	3.31
13	10.2	0.30	0.31	43	21.7	3.62	3.56
25	10.7	0.38	0.36	21	22.2	3.83	3.87
12	11.2	0.40	0.42	21	22.7	4.18	4.12
15	11.7	0.47	0.48	12	23.1	4.34	4.38
14	12.2	0.54	0.56	16	23.7	4.95	4.75
18	12.7	0.60	0.63	7	24.3	5.14	5.12
19	13.2	0.71	0.72	9	24.7	5.88	5.45
23	13.7	0.80	0.81	2	25.2	6.15	5.79
37	14.2	0.89	0.91	3	25.6	6.80	6.08
55	14.7	1.00	1.01	2	26.2	6.13	6.53
87	15.2	1.12	1.13	1	26.5	5.90	6.82
103	15.8	1.31	1.26	1	27.5	8.00	7.69
120	16.2	1.43	1.39	1	29.2	8.90	9.34
170	16.7	1.53	1.52				

[1] Actual averages for fish grouped by ½-inch intervals.

The empirical weights of whitefish at different lengths are shown graphically by dots in figure 3. The curve is a graph of the following equation obtained by fitting a straight line by least squares to the logarithms of the average lengths and weights:

$$W = 1.6643 \times 10^{-4} L,^{3.2408}$$

where W=weight in pounds,
and L=total length in inches.

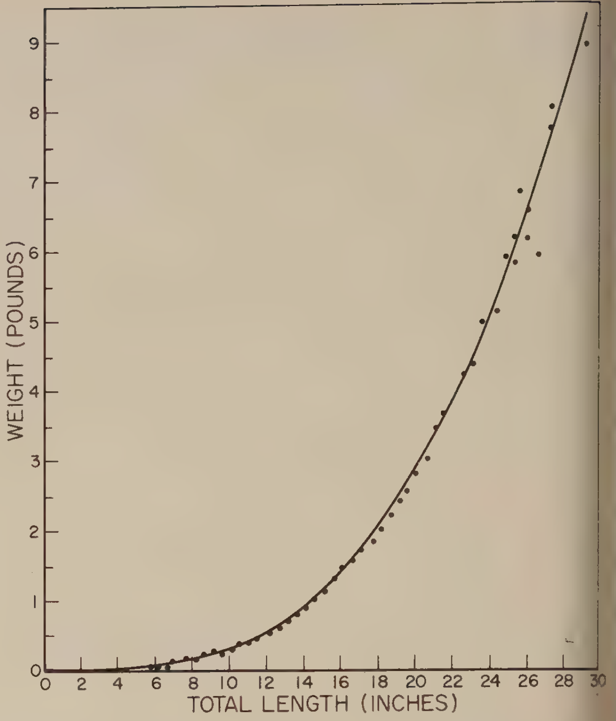


FIGURE 3.—Length-weight relation of Lake Superior whitefish. The curve represents the calculated weights and the dots the empirical weights.

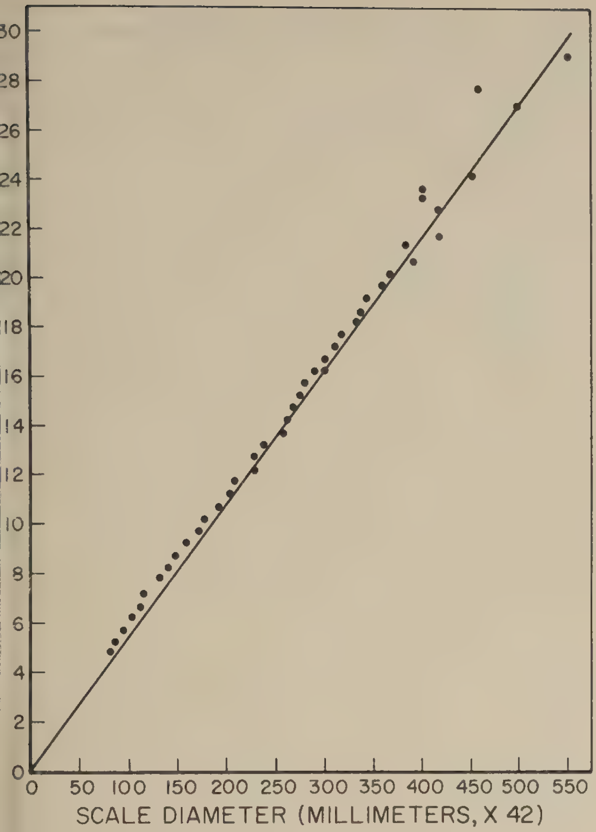
The length of the Lake Superior whitefish increases as the 3.2408 power of the length. The substantial departure of this power above 3 indicates a considerable increase of plumpness with increase of length.

The agreement between the calculated and empirical weights was generally good. The greatest discrepancies were among the larger fish where the numbers of individuals were small. The largest disagreement occurred at 26.5 inches where the empirical weight (5.90 pounds) was 0.92 pound below the calculated weight (6.82 pounds). Other disagreements between the calculated and empirical weights were without trend and did not exceed 0.72 pound among fish above 21.2 inches and 0.07 pound for fish less than 21.2 inches long.

CALCULATED GROWTH

BODY-SCALE RELATION

The body-scale relation of Lake Superior whitefish taken at Bayfield supports the earlier finding of Van Oosten (1923) that direct-proportion calculations of the length of whitefish based on diameter measurements of the scales are satis-



GURE 4.—Relation between body length and scale iameter of Lake Superior whitefish taken at Bayfield, 957–59. The line is a graph of the equation given in he text. The dots show the empirical averages by .5-inch intervals of total length.

tory. Key scales, taken from an exactly de- ed location, were not available, but scale samples noved from the same area of all fish are believed be reliable for the determination of a body- le regression.

The body-scale relation (table 10, fig. 4) con- ucted from records for 694 whitefish collected Bayfield is obviously linear. A straight line ed by least squares to the means of scale di- eters and lengths of fish had the equation:

$$L = 0.04443 + 0.5401\ S,$$

ere L=total length in inches,

d S=scale diameter (×42) in millimeters.

The intercept of 0.04 inch on the length axis so small it can be ignored; growth, accordingly, y be calculated by direct proportion. This ocedure was further justified by the fact that the values of the body-scale ratio remained nearly constant regardless of the length of the fish.

TABLE 10.—*Relation between body length (L) and the diameter measurement of scales (S) of Bayfield whitefish*

[Scale samples from 54 additional fish were not removed from the key area; these fish were not included in the study of the body-scale relation]

Number of fish	Total length [1] (inches)	Scale diameter (millimeters ×42)	Body-scale ratio [2] (×100)	Number of fish	Total length [1] (inches)	Scale diameter (millimeters ×42)	Body-scale ratio [2] (×100)
1	4.8	85	5.64	32	15.2	276	5.52
4	5.2	87	5.95	46	15.7	281	5.59
3	5.7	95	5.97	75	16.2	294	5.49
20	6.2	103	6.04	70	16.7	301	5.55
10	6.6	113	5.87	43	17.2	313	5.44
6	7.2	115	6.25	45	17.7	318	5.56
3	7.8	133	5.87	23	18.2	336	5.42
5	8.2	141	5.79	17	18.7	338	5.53
17	8.7	148	5.91	15	19.2	345	5.56
20	9.2	160	5.77	11	19.7	360	5.55
23	9.7	174	5.59	6	20.1	368	5.46
14	10.2	177	5.78	5	20.7	382	5.45
22	10.7	192	5.58	5	21.3	369	5.78
12	11.2	205	5.48	4	21.7	418	5.20
13	11.7	208	5.64	2	22.8	418	5.50
12	12.2	228	5.35	1	23.3	401	5.81
18	12.7	230	5.52	1	23.7	401	5.91
23	13.2	241	5.50	1	24.2	453	5.34
13	13.7	258	5.31	1	27.8	460	6.04
28	14.2	263	5.41	1	29.1	553	5.26
21	14.7	270	5.44				

[1] Means for fish within a 0.5-inch interval of total length.
[2] Means of the body-scale ratio computed for individual fish.

Body-scale data were inadequate for whitefish from other parts of Lake Superior because small fish were lacking in the samples. Preliminary observations suggest the possibility of slight differences between the body-scale relation of these fish and those from Bayfield. Because data were insufficient to test this possibility, calculations for all of the samples, regardless of locality, were made by direct proportion. Edsall (1960) described the body-scale relation of Munising Bay whitefish with a straight line that had an intercept of 1.486 inches on the length axis.

GROWTH IN LENGTH OF THE AGE GROUPS

The sexes have been combined for calculated growth of whitefish from the various ports. Sex records were lacking for most collections, but the comparison of the calculated growth of males and females, age group by age group, at Bayfield where sex data were available for most fish, disclosed no differences.

The major difficulties in the estimation of growth lay in the systematic decline in growth rate with increase of age at capture in collections from all four ports (tables 11, 12, 13, and 14). For example, first-year calculated lengths of whitefish taken at Bayfield in 1957 (table 11) decreased from 7.5 inches for age-group I to 4.2

TABLE 11.—*Calculated total length (inches) of whitefish taken at Bayfield in 1957 and 1959 and average calculated lengths for each year's collections and for the combined collections*

[In the bottom section the numbers of fish are in parentheses]

Age and year of capture	Number of fish	Calculated length at end of year of life									
		1	2	3	4	5	6	7	8	9	10
I 1957	2	7.5									
II 1957	22	5.8	10.3								
III 1957	73	5.4	8.8	12.6							
1959	6	5.3	9.9	14.2							
IV 1957	6	5.2	8.4	11.4	15.3						
1959	117	5.6	8.9	12.4	16.1						
V 1957	70	4.2	6.9	9.6	12.2	14.8					
1959	22	5.3	8.2	11.2	14.4	17.0					
VI 1957	55	4.2	6.7	8.9	11.1	13.6	15.9				
VII 1957	81	4.6	6.5	8.3	10.1	12.4	14.8	16.8			
VIII 1957	59	4.6	6.1	7.9	9.6	11.7	13.8	15.8	17.5		
IX 1957	3	4.8	6.9	8.0	9.7	11.8	14.0	16.1	18.3	19.7	
X 1957	1	4.4	6.3	8.2	9.8	11.2	13.2	14.8	16.6	17.9	18.6
Average:											
1957 [1]		4.7 (372)	7.3 (370)	9.5 (348)	10.8 (275)	13.1 (269)	14.8 (199)	16.4 (144)	18.1 (63)	19.5 (4)	20.2 (1)
1959		5.5 (145)	8.8 (145)	12.3 (145)	15.8 (139)	17.0 (22)					
1957, 1959 [2]		5.1	8.0	10.9	13.3	15.0	16.7	18.3	20.0	21.4	22.1

[1] Based on successive addition of grand average increments beyond the seventh year of life.

[2] Unweighted mean average lengths for the 1957 and 1959 samples through the first 5 years of life; lengths for later years obtained by successive addition of annual increments for the fish of the 1957 sample.

inches for age-group V. Second-year calculated lengths decreased from 10.3 inches for the II group to 6.1 inches for VIII group. Similar discrepancies occurred in the data for all of the collections. Second-year calculated lengths, for example, decreased from 11.6 inches for the II group to 7.9 inches for the VI group at Marquette (table 12), from 12.2 inches for the II group to 8.4 inches for the VII group at Whitefish Point (table 13), and from 11.7 inches for the II group to 8.0 inches for the V group at Dollar Settlement (table 14).

The high calculated lengths of the younger age groups and the low values for the older fish can be traced to two major sources: gear selection of the larger fish in the younger age groups, and the progressive destruction of the faster growing fish of a year class as they attain the legal length of 17 inches. Gear selection leads to overestimates of growth of the younger age groups, and the selective destruction of the faster growing fish modifies progressively the growth characteristics of the survivors, and thus leads to successively more severe underestimates of the growth that would occur if the stock were not subjected to this type of exploitation. The selective destruction can end only when the smallest members of the year class reach legal length.

A comparison of calculated lengths of whitefish taken by the *Siscowet* with those taken from commercial gear at Bayfield in 1959 (table 15) illustrates bias through gear selection. The calculated lengths of fish from the commercial samples were nearly always higher than the

TABLE 12.—*Calculated total length (inches) of whitefish taken off Marquette, 1957–59*

[In the bottom section the numbers of fish are in parentheses]

Age group	Number of fish	Calculated length at end of year of life									
		1	2	3	4	5	6	7	8	9	10
II	16	6.0	11.6								
III	115	5.9	9.7	13.9							
IV	153	5.6	9.0	12.6	16.7						
V	115	5.3	8.5	11.5	15.2	18.9					
VI	38	5.2	7.9	10.6	13.7	17.3	20.5				
VII	12	5.6	8.1	10.5	13.2	16.1	19.4	21.8			
VIII	5	5.3	8.0	11.1	14.2	17.8	20.9	23.0	24.3		
IX	1	4.5	6.6	8.6	10.1	11.2	13.2	17.0	18.9	23.1	
X	3	5.5	8.0	9.4	11.9	14.0	16.8	19.2	21.8	23.4	25.0
Grand average [1]		5.6 (458)	9.0 (458)	12.4 (442)	15.6 (327)	18.2 (174)	20.0 (59)	21.5 (21)	22.9 (9)	25.2 (4)	26.8 (3)

[1] Based on successive addition of mean increments in the 9th and 10th years of life.

BLE 13.—*Calculated total length (inches) of whitefish taken off Whitefish Point, 1957–59*

[In the bottom section the numbers of fish are in parentheses]

Age group	Number of fish	Calculated length at end of year of life						
		1	2	3	4	5	6	7
	1	6.8						
	27	6.8	12.2					
	178	6.7	11.7	15.1				
	94	6.7	10.6	14.3	17.8			
	31	6.4	10.5	14.2	17.8	20.9		
	7	5.5	8.7	12.8	15.9	19.0	22.3	
	2	5.1	8.4	11.8	14.9	17.5	19.8	21.4
Grand average [1]		6.6 (340)	11.2 (339)	14.7 (312)	17.6 (134)	20.4 (40)	21.7 (9)	23.3 (2)

Based on addition of the increments in the seventh year of life.

lculated lengths from the *Siscowet* samples.
ıe differences were particularly great for age-
oups III and V but were limited in age-group IV.
hitefish collected by the *Siscowet* were taken
ɔm small-mesh trawls (2½-inch-mesh body;
inch-mesh cod end) and experimental gill nets
th mesh sizes ranging from 1 to 5 inches by
inch intervals. The commercial samples were
ken from 4¾-inch-mesh pound nets and 4½-inch-
esh gill nets. Undoubtedly only the larger
embers of the younger age groups were re-
ned by the large meshes of the commercial
ar, whereas most sizes were retained by the
scowet gear.

The effect of the progressive destruction of the
ster growing fish is illustrated by records for
itefish samples collected in 1957 at Bayfield
June, July, and August (table 16). The
owth of members of the same age group taken
successive months differed widely. With few
ceptions, whitefish at age-groups V to VIII
ken earlier in the season had greater lengths at
pture and higher calculated lengths than did
those taken later. The shift was progressive; the lengths of fish taken in June were greater than for those taken in July; the lengths of fish taken in July were greater than for those taken in August. The length distributions of the age groups (table 17) also show a systematic decrease in size as the summer progressed. With only one exception (August V-group sample) the percentage of legal fish in each of the age groups decreased as the season advanced.

The pound net fishery for whitefish begins at Bayfield about mid-June, and legal-size fish are selected immediately from the population. As the season progresses the number of legal-size whitefish in the commercial catch, despite summer growth, declines until middle and late August when operations cease because production levels make it economically impossible to continue. In 1957, 44.7 percent of the whitefish in the entire June sample were legal size. In July, 37.9 percent were legal, and by August only 16.3 were legal, a reduction of 28.4 in the percentage since June.

Since the growth rate of the Bayfield whitefish is so slow, the number of legal-size fish taken from the fishery far exceeds the number of undersized fish growing to legal size during the early-summer fishing season.

Records on the progress of the season's growth (table 18) suggest that one-third or more of the total growth occurs after August 15 which is about the time that the heavy pound netting ends. This growth, though less than 1 inch, is sufficient to bring a good number of whitefish into legal-size range by the following spring when pound netting is resumed.

TABLE 14.—*Calculated total length (inches) of whitefish taken off Dollar Settlement, 1957–59*

[In the bottom section the numbers of fish are in parentheses]

Age group	Number of fish	Calculated length at end of year of life									
		1	2	3	4	5	6	7	8	9	10
	1	7.0									
	40	6.3	11.7								
	95	6.3	9.9	14.2							
	47	6.0	9.1	12.5	16.1						
	55	5.1	8.0	10.6	14.1	17.2					
	10	5.3	8.6	11.3	13.4	16.5	19.1				
	4	5.4	8.1	10.4	12.3	14.8	17.7	20.2			
I.	1	5.5	9.5	11.5	13.1	15.7	17.1	18.7	19.4		
	1	5.0	8.1	9.9	11.4	14.7	18.1	22.1	23.4	24.4	25.8
Grand average [1]		5.9 (254)	9.5 (253)	12.7 (213)	14.8 (118)	16.9 (71)	18.6 (16)	20.3 (6)	21.4 (2)	22.4 (1)	23.8 (1)

Based on successive addition of the mean increments in the 9th and 10th years of life.

TABLE 15.—*Calculated total lengths (inches) of three age groups of whitefish taken by the M/V* Siscowet *and from Commercial gear at Bayfield, 1959*

Age group and source of sample		Number of fish	Calculated length at end of year of life				
			1	2	3	4	5
III	*Siscowet*	14	4.8	8.5	11.5	--------	--------
	Commercial	6	5.3	9.9	14.2	--------	--------
IV	*Siscowet*	21	5.5	9.0	12.3	15.4	--------
	Commercial	117	5.6	8.9	12.4	16.1	--------
V	*Siscowet*	18	5.3	7.7	10.4	13.0	15.4
	Commercial	22	5.3	8.2	11.2	14.4	17.0

Discrepancies of calculated length of the type shown by Lake Superior whitefish have been observed repeatedly among fish sorted about a size limit or taken by highly selective gear. Numerous explanations of discrepancies in calculated lengths can be found in the literature. Some have been traced to the use of incorrect formulas for growth calculation, but where the body-scale relation has been determined accurately, investigators generally have agreed that gear selectivity and destruction of the more rapidly growing individuals by the fishery are the two major sources of bias. Discussions of this problem may be found in Deason and Hile (1947) and El-Zarka (1959).

GENERAL GROWTH IN LENGTH

The information on gear selectivity and selective destruction of the rapidly growing fish given in the previous section makes it obvious that any estimate of general growth is of necessity an approximation. Since the two major sources of bias are to an unknown degree compensating, the estimate of general growth for each locality is based on all available fish. The *Siscowet* samples have been omitted from the general growth studies in order to permit comparisons among the net-run collections from commercial gear at the various ports.

The 1957 and 1959 Bayfield samples have been combined even though differences were wide between the sizes at capture and the calculated lengths of the two collections. As was explained in the section on age and size at capture, the differences most probably can be attributed to a period of exceptionally good growth in 1954–57.

TABLE 16.—*Size at capture and calculated total lengths (inches) of four age groups in samples of whitefish collected at Bayfield in different months, 1957*

Age and Date of collection		Number of fish	Average length at capture	Calculated length at end of year of life							
				1	2	3	4	5	6	7	8
V	June 13	21	16.4	4.4	7.0	10.0	13.0	16.4	--------	--------	--------
	July 22	32	15.2	4.3	7.0	9.3	12.2	14.4	--------	--------	--------
	Aug. 15	16	15.1	4.2	6.5	8.9	11.1	13.7	--------	--------	--------
VI	June 13	12	17.9	4.6	7.1	9.6	12.5	15.3	17.9	--------	--------
	July 22	28	16.6	4.4	6.9	9.0	11.1	13.6	15.7	--------	--------
	Aug. 15	14	16.0	4.2	6.4	8.1	9.9	12.1	14.7	--------	--------
VII	June 13	24	18.4	4.6	6.7	8.7	10.9	13.4	15.8	18.4	--------
	July 22	41	17.3	4.7	6.6	8.4	10.3	12.3	14.6	16.4	--------
	Aug. 15	16	16.4	4.6	6.1	7.7	9.4	11.4	13.5	15.3	--------
VIII	June 13	21	18.9	4.5	6.3	8.3	10.1	12.3	14.6	16.8	18.9
	July 22	27	17.5	4.6	6.1	7.9	9.6	11.6	13.7	15.5	16.9
	Aug. 15	11	17.4	4.5	5.9	7.3	9.0	10.7	12.5	14.5	16.4

TABLE 17.—*Length distribution of the age groups of samples of whitefish collected at Bayfield in different months, 1957*

Total length (inches)	V-group			VI-group			VII-group			VIII-group		
	June	July	August	June	July	August	June	July	August	June	July	August
12.0–12.9	--------	--------	1	--------	--------	--------	--------	--------	--------	--------	--------	--------
13.0–13.9	--------	--------	2	--------	--------	--------	--------	--------	1	--------	--------	--------
14.0–14.9	2	13	4	--------	1	1	--------	1	2	--------	--------	--------
15.0–15.9	5	14	5	--------	4	6	--------	3	8	--------	1	--------
16.0–16.9	9	5	3	3	14	5	2	14	5	--------	5	4
17.0–17.9	2	--------	1	3	7	1	9	10	--------	4	15	5
18.0–18.9	2	--------	--------	4	2	1	5	11	--------	7	5	1
19.0–19.9	1	--------	--------	1	--------	--------	5	--------	--------	7	1	1
20.0–20.9	--------	--------	--------	1	--------	--------	1	2	--------	2	--------	--------
21.0–21.9	--------	--------	--------	--------	--------	--------	.2	--------	--------	--------	--------	--------
22.0–22.9	--------	--------	--------	--------	--------	--------	--------	--------	--------	1	--------	--------
Total number	21	32	16	12	28	14	24	41	16	21	27	11
Average length	16.4	15.2	15.1	17.9	16.6	16.0	18.4	17.3	16.4	18.9	17.5	17.4
Percentage, legal size	23.8	0.0	6.3	75.0	32.1	14.3	91.7	56.1	18.8	100.0	77.8	63.6

BLE 18.—*Amount of season's growth in length (inches) of four age groups of Bayfield whitefish up to and following August 15, 1957*

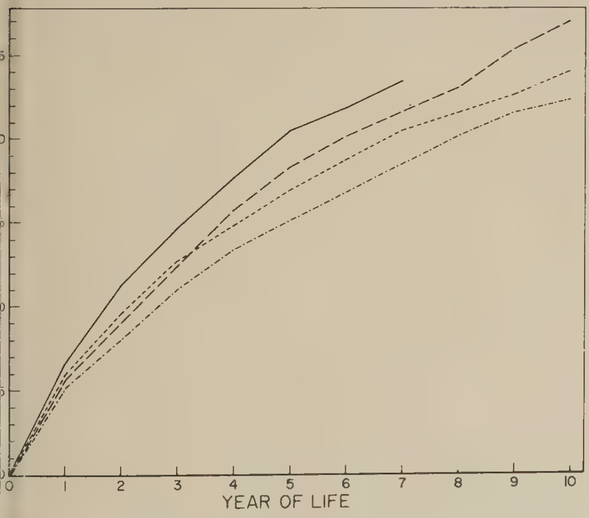
Age group	Growth to Aug. 15	Full season's growth[1]	Growth after Aug. 15	Percentage of total growth
	1.4	2.3	0.9	39
	1.3	2.0	.7	35
	1.1	1.7	.6	35
	1.0	1.4	.4	29

Determined from the next higher age group in the same collection.

Growth in length of Lake Superior whitefish ried considerably according to port (table 19, . 5). Bayfield whitefish were by far the slowest owing. The first-year calculated length was inches. The annual increments decreased m 2.9 inches in the second and third years to inch in the tenth, at which time the fish re 22.1 inches long.

The whitefish from Marquette were considerly faster growing. These fish attained an erage length of 5.6 inches in the first year, and rly rapid growth continued through the fifth ar of life when their average calculated length s 18.2 inches. Marquette whitefish were 26.8 hes long at the end of their tenth growing son.

The Whitefish Point whitefish were by far the test growing in the four areas studied. At the d of the first year the fish averaged 6.6 inches ng. The annual increments decreased slowly m 4.6 inches in the second year to 2.8 inches in the fifth at which time the fish averaged 20.4 inches (compared to 15.0 inches at Bayfield). By the end of the seven growing seasons, the Whitefish Point whitefish were 23.3 inches long. The samples included no fish older than age-group VII.



URE 5.—Calculated length of Lake Superior whitefish according to port. Whitefish Point, solid line; Marquette, long dashes; Dollar Settlement, short dashes; Bayfield, dots and dashes.

TABLE 19.—*Calculated total length (inches) of Lake Superior whitefish according to port*

[The collections from the different years have been combined]

Year of life	Bayfield		Marquette		Whitefish Point		Dollar Settlement	
	Length	Increment	Length	Increment	Length	Increment	Length	Increment
1	5.1	5.1	5.6	5.6	6.6	6.6	5.9	5.9
2	8.0	2.9	9.0	3.4	11.2	4.6	9.5	3.6
3	10.9	2.9	12.4	3.4	14.7	3.5	12.7	3.2
4	13.3	2.4	15.6	3.2	17.6	2.9	14.8	2.1
5	15.0	1.7	18.2	2.6	20.4	2.8	16.9	2.1
6	16.7	1.7	20.0	1.8	21.7	2.9	18.6	1.6
7	18.3	1.6	21.5	1.5	*23.3	1.6	20.3	1.7
8	*20.0	1.7	22.9	1.4	--------	------	21.4	1.1
9	*21.4	1.4	*25.2	2.3	--------	------	*22.4	1.0
10	*22.1	0.7	*26.8	1.6	--------	------	*23.8	1.4

Asterisks indicate lengths based on the successive addition of grand average increments.

Dollar Settlement whitefish were longer than the Marquette stocks for the first 3 years, but were the shorter in the subsequent 7 years. Dollar Settlement whitefish attained an average length of 5.9 inches in the first year of life, and 16.9 inches by the end of the fifth year. Their calculated length after 10 growing seasons was 23.8 inches. The growth rate of the Dollar Settlement stock was clearly different from that of the Whitefish Point fish even though the grounds are barely 30 miles apart. Preliminary examination of scale samples collected in 1960 from Dollar Settlement and Whitefish Point further demonstrated faster growth of fish from Whitefish Point; the differences were not as pronounced, however, as in the 1957–59 samples.

The differences in the calculated growth of whitefish taken off different ports, along with the differences in age composition and size at capture of the commercial catch, were sufficiently great and consistent to suggest that a number of distinct stocks of whitefish inhabit Lake Superior. This belief is given further support by the findings of Edsall (1960) on the very slow growth of whitefish in Munising Bay, Lake Superior. The Munising Bay whitefish averaged 5.5 inches long after the first growing season, but second-year growth amounted to only 1.7 inches, and no annual increment exceeded 1.0 inch after the third year or

0.5 inch after the twelfth. The highest calculated length attained was 16.7 inches in 16 years.

The major differences in growth among the four open-lake stocks of Lake Superior whitefish occur during the first few years of life. After the fifth year the annual increments of growth agree reasonably well. It would appear that the factors controlling growth rates are most effective during the first few years of life.

The order of the four stocks with respect to calculated length was the same for all years of life except in the samples from Marquette and Dollar Settlement (fig. 5). The Bayfield fish had the shortest and the Whitefish Point fish the longest calculated lengths in all possible comparisons, but the position of fish from Marquette and Dollar Settlement was reversed as growth proceeded. The differences in calculated lengths between whitefish from Bayfield and Whitefish Point were very large. At the end of 7 years, the calculated length of the Whitefish Point stock was 5.0 inches longer than that of the Bayfield whitefish.

GENERAL GROWTH IN WEIGHT

The weights of table 20 (see also fig. 6) were computed by means of the general length-weight equation given on p. 86 and correspond exactly with lengths of table 19. All questions relating to the reliability of the calculated lengths of table 19 apply, therefore, to the calculated weights.

The calculated weights differed little at the end of the first year, but in subsequent years wide differences developed among fish from the several ports. Since the calculated weights were computed from the calculated lengths, the Bayfield whitefish exhibited the slowest growth in weight. Increments in individual years of life were small at Bayfield (0.04 pound the first year to 0.70 pound in the ninth). Bayfield stocks did not reach 1 pound until the fifth year of life and weighed only 3.85 pounds after 10 years.

TABLE 20.—*Calculated weight (pounds) at the end of each year of life of Lake Superior whitefish according to port*

[Weights were computed from the calculated lengths of table 19 by means of the general length-weight equation]

Year of life	Bayfield		Marquette		Whitefish Point		Dollar Settlement	
	Weight	Increment	Weight	Increment	Weight	Increment	Weight	Increment
1	0.04	0.04	0.05	0.05	0.07	0.07	0.05	0.05
2	.14	.10	.20	.15	.42	.35	.25	.20
3	.40	.26	.57	.37	1.01	.59	.63	.38
4	.72	.32	1.20	.63	1.80	.79	1.02	.39
5	1.05	.33	2.00	.80	2.90	1.10	1.57	.55
6	1.52	.47	2.70	.70	3.56	.66	2.13	.56
7	2.02	.50	3.40	.70	4.48	.92	2.88	.75
8	2.70	.68	4.20	.80	--------	------	3.37	.49
9	3.40	.70	5.79	1.59	--------	------	3.95	.58
10	3.85	.45	7.05	1.26	--------	------	4.80	.85

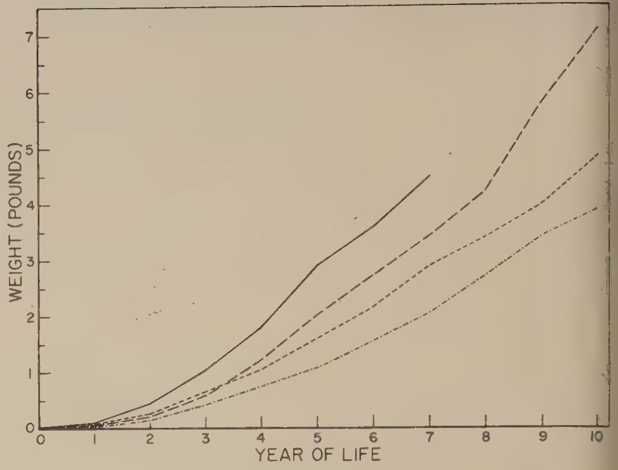


FIGURE 6.—Calculated growth in weight of Lake Superior whitefish according to port. Whitefish Point, solid line; Marquette, long dashes; Dollar Settlement, short dashes; Bayfield, dots and dashes.

The Marquette whitefish grew considerably faster in weight than the Bayfield stock. These fish reached 1 pound during the fourth growing season, and by the tenth they had reached 7.05 pounds. The annual increments of weight increased steadily from 0.05 pound in the first year to 0.80 pound in the fifth year. Between the fifth and eighth years the increments varied only from 0.70 to 0.80 pound. During the ninth year the increment was 1.59 pounds, and in the tenth it was 1.26 pounds.

Growth was faster at Whitefish Point, of course, than at any other port. The fish reached 1 pound at the end of the third growing season, and by the seventh year they weighed 4.48 pounds. Annual increments exceeded 0.5 pound in each year after the second.

The growth in weight of Dollar Settlement stocks was better than Bayfield fish but slower than the Marquette (after 3 years) and Whitefish Point stocks. Four years were required for the fish to reach 1 pound, and at the end of 10 years they weighed 4.80 pounds. The annual increments varied from 0.05 pound in the first year to 0.85 pound in the tenth year of life.

TABLE 21.—*Growth in total length (inches) of whitefish in different parts of the Great Lakes*

rces of data: Lake Ontario, Hart (1931); Lake Erie, Van Oosten and Hile (1949); Lake Huron, Van Oosten (1939); Lake Michigan, Roelofs (1958); Lake Superior, Munising Bay, Edsall (1960). Records are not carried beyond 10 years]

Area	Calculated length at end of year of life									
	1	2	3	4	5	6	7	8	9	10
e Ontario [1]	----------	----------	9.4	12.0	15.4	17.9	19.1	20.4	21.0	22.8
e Erie	6.9	12.7	16.1	18.1	19.6	20.7	21.4	22.1	22.8	23.2
e Huron	5.0	8.9	12.3	16.1	19.2	21.4	22.9	23.9	24.8	25.3
e Michigan:										
Big Bay de Noc	5.6	9.4	13.8	17.9	----------	----------	----------	----------	----------	----------
South Fox Island	4.3	7.0	9.9	13.2	----------	----------	----------	----------	----------	----------
e Superior:										
Bayfield	5.1	8.0	10.9	13.3	15.0	16.7	18.3	20.0	21.4	22.1
Marquette	5.6	9.0	12.4	15.6	18.2	20.0	21.5	22.9	25.2	26.8
Munising Bay	5.5	7.2	8.4	9.4	10.1	10.8	11.5	12.1	12.9	13.6
Whitefish Point	6.6	11.2	14.7	17.6	20.4	21.7	23.3	----------	----------	----------
Dollar Settlement	5.9	9.5	12.7	14.8	16.9	18.6	20.3	21.4	22.4	23.8

Actual lengths at capture during growing season subsequent to indicated year.

ROWTH OF WHITEFISH IN LAKE SUPERIOR AND OTHER GREAT LAKES

The records of growth of whitefish in other eat Lakes localities were published originally h various measurements and units, and some esentations included no calculated lengths. rtain adaptations were required and some ex- nations are needed to permit an instructive dy of the data of table 21. The lengths for e Lake Ontario whitefish represent actual gths at capture for fish collected during the licated year of life; they have been converted total length from the standard lengths given Hart (1931). The data for Lake Huron and ke Erie are from a table in Van Oosten and le (1949).

The differences in growth among the various cks of Great Lakes whitefish do not allow a ar ranking for individual populations. The ations among the stocks shifted according to e, and not one group was consistently the ter or slower growing population. The white- h from South Fox Island grew only 4.3 inches ring the first year of life but by the end of the rth year they were 13.2 inches long. Munising y whitefish grew 5.5 inches the first year but l not reach 13.0 inches until the tenth year of . The growth of whitefish from Whitefish int, Marquette, and Dollar Settlement com- red closely with the growth of Lake Erie, Lake ron, and Big Bay de Noc stocks. Again, the a ions shifted according to age, but all of these cks were among the fastest growing whitefish the Great Lakes. The growth of the Bayfield itefish was similar to that of the Lake Ontario stock, faster growing than Munising Bay and South Fox Island fish but slower than the other populatiosn.

SEX RATIO AND MATURITY

SEX RATIO

Usable data on the sex ratio of Lake Superior whitefish are available only for part of the Bayfield samples of 1957 and 1959 (table 22). The data from the samples for the 2 years were so similar that the collections have been combined. Fish of age-group I were omitted from this study because of uncertainties in sex determination. With the exception of age-groups V and VII, the number of males exceeded the number of females in age-groups II–VIII. The advantage of the males over the females was small—not over 58.1 percent males (age-group III). Age-groups IX and X were represented by very small numbers of fish, but males were scarce at these ages—only one male in a total of seven fish. The percentage of male whitefish in samples from Lake Huron (Van Oosten, 1939) and Lake Erie (Van Oosten and Hile, 1949) decreased with increase of age.

In the entire Bayfield sample, all ages combined, the sexes were almost equally represented (51.5 percent males).

SIZE AND AGE AT MATURITY

All whitefish from Bayfield shorter than 14.5 inches were immature, and all fish longer than 17.4 inches were mature. The first mature male appeared in the 14.5- to 14.9-inch group (table 23). The percentage of mature males reached 57.1 percent at 16.0–16.4 inches, and all of the males were mature at lengths greater than 16.9 inches.

Table 22.—*Sex ratio of whitefish taken at Bayfield*

[Based on the combined collections of 1957 and 1959]

Age group	Number of males	Number of females	Percentage males
II	35	29	54.7
III	50	36	58.1
IV	54	47	53.5
V	46	47	49.5
VI	25	24	51.0
VII	38	46	45.2
VIII	32	30	51.6
IX	-----	3	0
X	1	3	25.0
All ages	281	265	51.5

Table 23.—*Relation of length to maturity of whitefish taken at Bayfield in July and August 1957*

[Data on maturity were not recorded for all individuals. All fish shorter than 14.5 inches were immature, and all longer than 17.4 inches were mature]

Length (inches)	Males			Females		
	Number immature	Number mature	Percentage mature	Number immature	Number mature	Percentage mature
14.5–14.9	5	1	16.7	7	0	0
15.0–15.4	8	2	20.0	6	0	0
15.5–15.9	5	2	28.6	8	0	0
16.0–16.4	6	8	57.1	8	7	46.7
16.5–16.9	1	10	90.9	5	11	68.8
17.0–17.4	0	12	100.0	1	5	83.3

The first mature females appeared at 16.0–16.4 inches, and all females longer than 17.4 inches were mature. First maturity of males occurred at a length 1.0 inch shorter than in females, and 100-percent maturity of males occurred at a length 0.5 inch shorter than in females.

The youngest mature fish of each sex belonged to age-group V (table 24), and all whitefish older than age-group VII were mature. Among age-groups V–VII the percentage maturity of males was consistently higher than for females of corresponding age. The mature fish of each sex without exception were longer than the immature fish of the same age group.

The scanty data on sexual maturity from other ports are inadequate for detailed study, but they suggested that the faster growing whitefish mature at a greater length and a lower age. Alm (1959) held that fish which have particularly slow growth may mature at a higher age but at a length which is below that of faster growing specimens. Comparisons of length and age at maturity of Bayfield whitefish with those of whitefish from other localities support this argument. Munising Bay whitefish (Edsall, 1960), which grow much more slowly than the Bayfield stock, exhibit first maturity at 11.5 inches and 100-percent maturity at 15.0 inches. All Munising Bay whitefish younger than age-group VII were immature, and some were still immature as age-group XI. In direct contrast, Van Oosten (1939) reported first maturity for males at 17.8 inches and for females at 18.3 inches in Lake Huron. All of the males were mature at 20.1 inches, and all of the females at 21.5 inches. All male whitefish younger than age-group III and females younger than age-group IV were immature, and all males older than age-group V and females older than VI were mature. It appears, then, that among fish of the same length, those from stocks with the slower growth are the more likely to be mature, and among fish of the same age those from stocks with the more rapid growth are the more likely to be mature.

Table 24.—*Length of mature and immature whitefish of three age groups taken off Bayfield in July and August 1957*

[Number of fish in parentheses. All whitefish younger than age-group V were immature, and all older than age-group VII were mature]

Sex and state of gonads	Calculated length at last annulus		
	V	VI	VII
Male:			
Mature	15.4	17.0	17.3
	(3)	(15)	(20)
Immature	15.0	15.2	16.4
	(24)	(6)	(2)
Percentage mature	11.1	71.4	90.9
Female:			
Mature	17.2	16.6	17.7
	(1)	(9)	(21)
Immature	15.1	16.0	15.8
	(16)	(11)	(10)
Percentage mature	5.9	45.0	67.7

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FLUENCE OF WATER VELOCITY UPON ORIENTATION AND PERFORMANCE OF ADULT MIGRATING SALMONIDS

By Charles R. Weaver, *Fishery Biologist*
Bureau of Commercial Fisheries

ABSTRACT

ıring the months of August and September 1957 a s of experiments were conducted at Bonneville ,, to determine (1) how adult migrating salmonids ond to differences in flow velocity, (2) how they per- in two relatively high-velocity flows, and (3) how elocity of flow influences their rate of movement. ven a choice of entering either of two parallel chan- arrying flows of different velocities, steelhead trout *no gairdneri*), chinook salmon (*Oncorhynchus wytscha*), and silver salmon (*O. kisutch*) generally onstrated a preference for the channel with the er velocity flow. The magnitude of the response d between species and with velocities of the choice ition.

e performances of steelhead trout and chinook on were examined in flow velocities of 13.4 and 15.8 feet per second by determining the distance they could achieve in an 85-foot channel. Although there was considerable variation in the distances attained by individual fish at each velocity, steelhead trout were generally more successful in negotiating these velocities than chinook salmon. Larger fish of both species were more successful in negotiating the two flows than smaller fish. Both species performed better in the 13.4 feet per second flow than in the 15.8 f.p.s. flow.

Rates of movement of steelhead trout, chinook salmon, and silver salmon were measured in velocities ranging from 2 to 15.8 f.p.s. Rates of movement varied with species, size of fish, and velocity. Maximum observed swimming speeds are given for each species and various factors affecting rate of movement are discussed.

ne increasing demand for greater utilization ater resources in the Pacific Northwest has ted in plans for the construction of many dams on the Columbia River and its tribu- s. One of the major problems arising from e dams is that of preserving the valuable romous fish populations indigenous to these rs. Although there are several important cts to the problem, one which is of primary ern is ensuring that the adult fish, migrating the ocean to their fresh-water spawning nds, are provided safe passage over these acles. In view of the number of dams which e fish will eventually have to surmount before ing their destinations, it is extremely impor- to ensure that the passage facilities provided ch dam (including temporary passage during truction) are designed to operate as efficiently ossible. The cumulative effect of even minor s or delays at each dam could seriously jeopardize the perpetuation of this valuable fishery resource. The material reported upon in this paper represents one phase of a research program being conducted by the Bureau of Commercial Fisheries (reviewed by Collins and Elling, 1961) under contract to the U.S. Army Corps of Engineers,[1] to gain more precise knowledge of the principles involved in adult fish passage.

Although fish passage requirements may vary with the nature of the obstacle to be bypassed, the basic problems entailed in achieving efficient passage are: (1) attracting the migrating fish into the fishway entrance without delay and (2) providing conditions which will promote a normal rate of movement through the facility without taxing the physical capacities of the fish. The

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[1] Research financed by the U.S. Army Corps of Engineers as part of a broad program of research to provide design criteria for more economical and more efficient fish-passage facilities at Corps projects on the Columbia River.

purpose of these experiments was to acquire a better understanding of how the velocities of fishway flows may be related to these problems. The following three types of experiments were conducted: velocity-preference, high-velocity, and rate-of-movement. The objectives were (1) to examine the orientative influence of water velocity upon adult migrating salmonids to determine how the relative attractiveness of fishway entrances may be influenced by the velocities of adjacent flows, (2) to examine the performance of these fish at two relatively high-velocity flows to gain a better idea of the maximum water velocities which might be tolerated in fishways or passage channels, and (3) to measure the rate of movement of the fish in flows of various velocities to determine which velocities might be more conducive to a uniform rate of passage through fishway channels.

The work was conducted at the Fisheries-Engineering Research Laboratory at Bonneville Dam on the Columbia River during the months of August and September 1957. Steelhead trout (*Salmo gairdneri*), fall chinook salmon (*Oncorhynchus tshawytscha*), and silver salmon (*O. kisutch*) were the salmonids used in the experiments.

RESEARCH LABORATORY

The laboratory is located immediately below the north end of the spillway section of Bonneville Dam adjacent to the Washington shore fishway (fig. 1). The laboratory and its entrance and exit fishways form a bypass around a short section of the main fishway (fig. 2). This unique feature permits fish to be collected, subjected to various types of experiments within the laboratory, and returned to the main fishway without being handled at any time.

The laboratory is composed of a collection pool where fish are collected prior to testing, an ex-

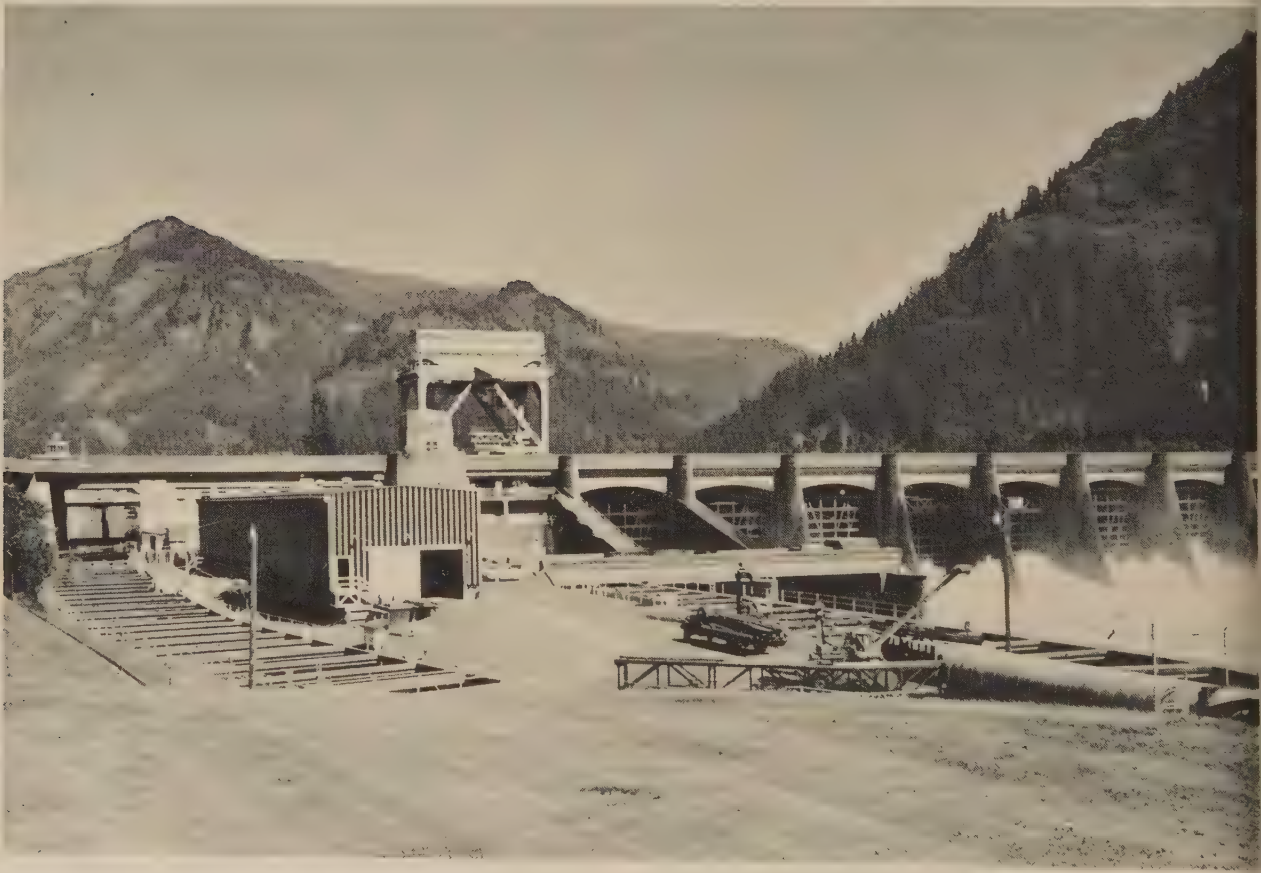


Figure 1.—Research laboratory showing Washington shore fishway in the foreground and section of main dam in background.

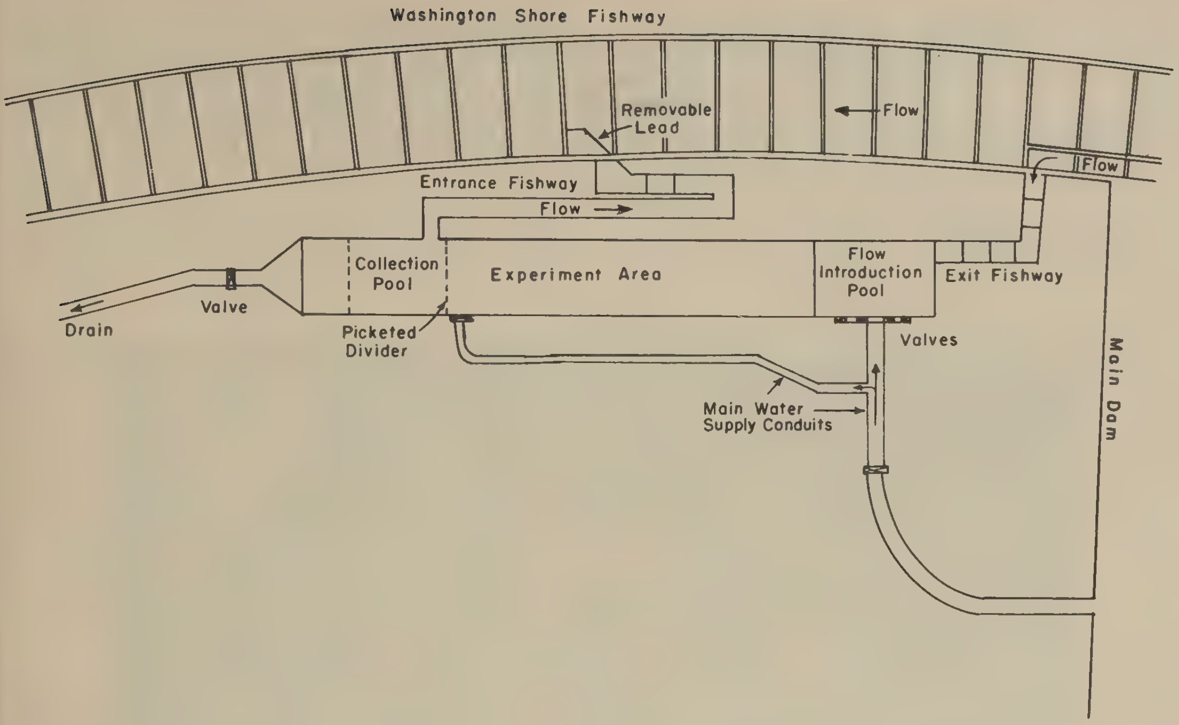


FIGURE 2.—Plan of research laboratory showing the basic components.

imental area which can be modified to provide variety of experimental conditions, and a w-introduction pool where water is introduced o the laboratory. Water is supplied from two rces. The main source, capable of supplying roximately 200 cubic feet per second, comes ectly from the forebay of the dam through a ge conduit. The secondary source, approx- ately 20 c.f.s., is drawn from the Washington re fishway to supply the facility exit fishway. e main water supply is distributed through aller conduits to the flow-introduction pool, collection pool, and other portions of the ility by manipulation of appropriate valves.

Vater is discharged from the laboratory through 8-inch drain conduit at the downstream end of laboratory and through the entrance fishway. scharge through the drain conduit is controlled an electrically operated drain valve. Any ired water level can be maintained in the lab- tory by proper adjustment of valves.

LOCITY-PREFERENCE EXPERIMENTS

METHODS AND MATERIALS

The method employed in these experiments s patterned after the one used by Collins (1952) in his studies of factors influencing the orientation of alewives (*Alosa pseudoharengus*) and glut herring (*A. aestivalis*). As the migrating fish passed through the laboratory they were presented with a choice of entering either of two channels. During control experiments the velocities of the flows in the two channels were equal; in test experiments the velocity of the flow in one channel was always greater than the other. The responses of the fish to the various test and control conditions were measured by the number of fish entering each channel.

Experimental Area

The basic experimental area of the facility was modified for these experiments to provide a choice or introductory area, 25 feet long and 11 feet wide, joining two parallel channels each 85 feet long and 5 feet wide (figs. 3 and 4). The channels, which will be referred to hereafter as the north and south channels, were centered in the experimental area and were separated by a common center wall 1 foot thick. The downstream end of the center wall was provided with a tapered hydrofoil to converge the two channel flows smoothly as they entered the choice area.

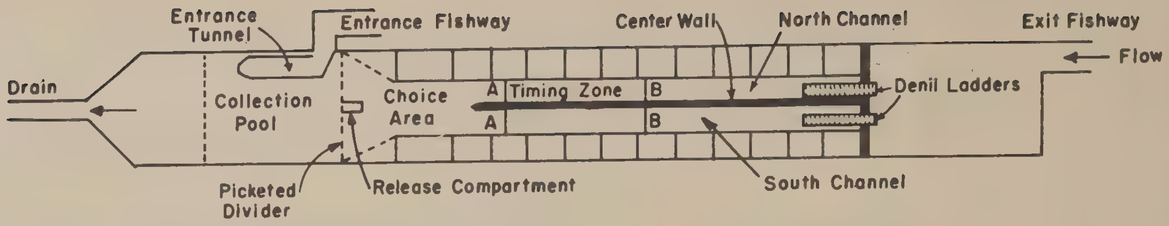

Entrance Tunnel
Entrance Fishway
Center Wall
North Channel
Exit Fishway
Flow
Drain
Collection Pool
Choice Area
A
Timing Zone
B
A
B
Denil Ladders
Picketed Divider
Release Compartment
South Channel

FIGURE 3.—Sketch of laboratory showing experimental area modified for the velocity-preference experiments.

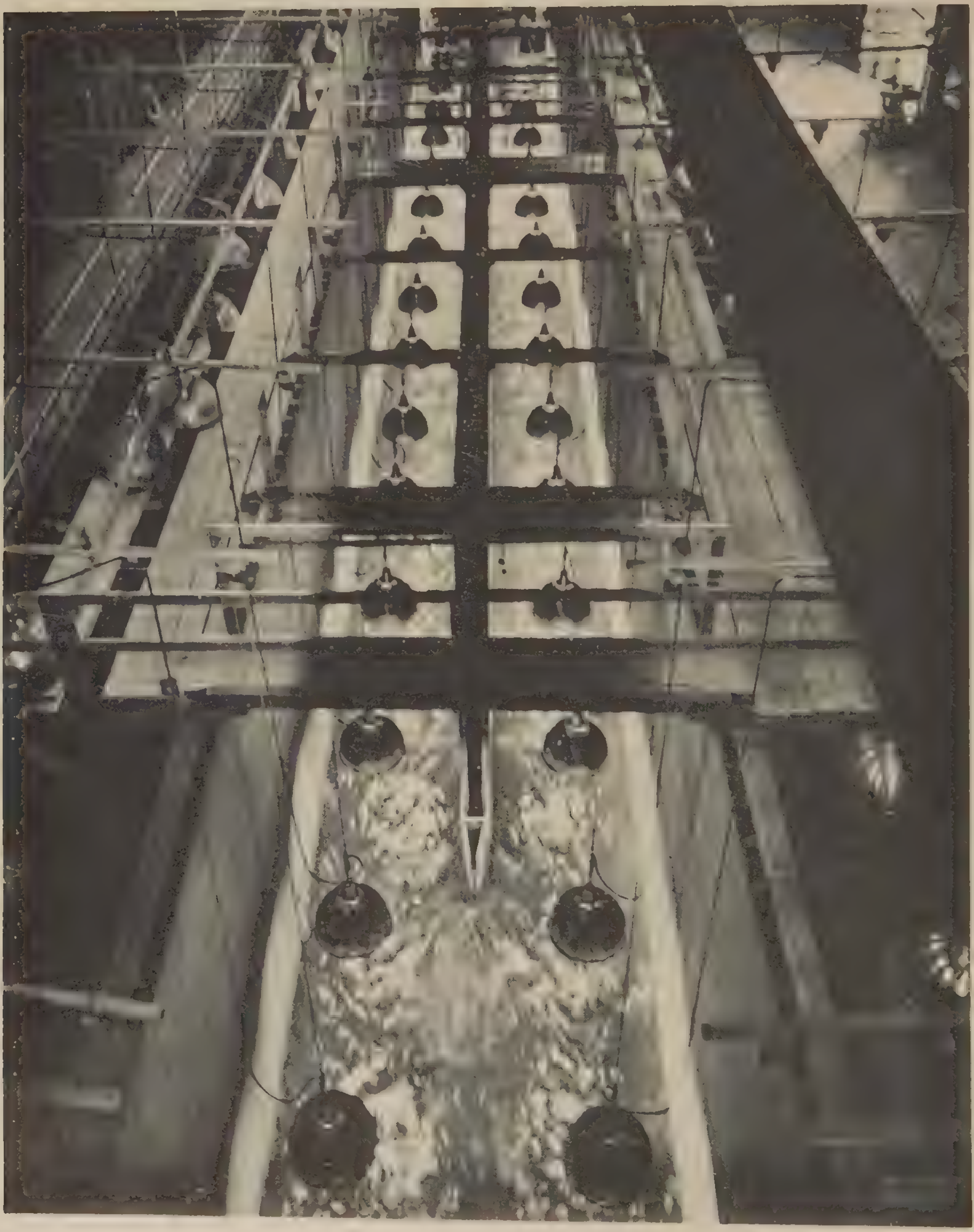


FIGURE 4.—View of the two channels and choice area during a control test. The velocity of flow in each channel is 4 f.p.s.

toplogs at the upstream end blocked the flow ough the two areas outside of the channels 3). The downstream ends of these areas e open, allowing them to backfill when water introduced into the area. Screens prevented from entering these areas.

he walls and floors of the channels and choice were painted light brown to provide a uni- n background throughout the experimental .

raulic Conditions

Vater velocities in the two channels were con- led independently by regulating the quantity ater admitted to them from the flow introduc- pool. This was accomplished by employing escribed arrangement of stoplogs at the up- am ends of the channels and maintaining the per water level in the flow-introduction pool. e the channel floors were level (zero slope) and water at the downstream end of the two chan- was maintained at nearly the same depth by lation of the collection pool level, the ratio of velocities of the two channels was equal to the of the quantities of water flowing through the channels. That is to say, if the velocity s.) of one channel was twice as great as the r, then the quantity of water flowing through channel (c.f.s.) would also be twice as great.

elocities approximating 2, 4, 6, and 8 f.p.s. utilized in these experiments. Table 1 lists various combinations of these velocities which were tested and gives the actual mean water velocities and depths as they were measured at the downstream end of the channels.

Hydraulic conditions within the channels and choice area varied with the velocity of the flow. At velocities of 2 and 4 f.p.s. uniform flow was maintained throughout the channels and choice area. At 6 and 8 f.p.s. velocities, standing waves were created within the channels and choice area (fig. 5). The position of these waves in relation to the channel and choice area walls remained fixed once the flows had become established. The structure shown at the upstream end of each channel in figure 5 are adjustable Denil-type ladders, which were provided to ensure that the fish would have no difficulty in negotiating the turbulent overfall created by the stoplogs.

Figure 6 illustrates the velocity gradients occurring in the choice area during the various tests at a point approximately 8 feet upstream from the release compartment. Velocities were measured with a Price current meter. Mean velocities were determined from measurements taken vertically at 4-inch intervals.

E 1.—*List of six test conditions and four control conditions utilized in the velocity-preference experiments*

ndition	Desired velocity		Actual velocity [1]		Depth of water [1]	
	High-velocity channel	Low-velocity channel	High-velocity channel	Low-velocity channel	High-velocity channel	Low-velocity channel
	F.p.s.	*F.p.s.*	*F.p.s.*	*F.p.s.*	*Feet*	*Feet*
	8	2	8.14	1.91	1.7	1.9
	8	4	8.03	3.96	1.7	1.8
	8	6	8.09	5.91	1.7	1.7
	6	2	6.00	1.95	1.8	1.9
	6	4	6.02	3.96	1.7	1.9
	4	2	3.98	2.00	1.9	1.9
	North channel	South channel	North channel	South channel	North channel	South channel
l.	2	2	2.03	2.01	1.9	1.9
	4	4	3.93	3.96	1.9	1.9
	6	6	5.97	6.04	1.7	1.7
	8	8	8.36	8.19	1.7	1.7

[1] an velocities derived from measurements taken during individua f each condition. Both velocities and water depths were measured at vnstream ends of the channels (fig. 5).

Release Compartment

Fish were introduced into the choice area through a release compartment 18 inches wide by 48 inches long by 18 inches deep. The compartment was mounted on the upstream face of the picketed divider in line with the center of the choice area (fig. 3). Fish entered the compartment through a sliding gate in the picketed divider and were released into the choice area by means of a second sliding gate at the upstream end of the compartment. The compartment was equipped with a false bottom or brail which could be raised to bring the fish near the water surface to facilitate the identification of species and estimation of length.

Efforts were made to achieve as near perfect symmetry as possible in the components of the release compartment and in the surrounding choice area to ensure that the fish would not perceive any visual stimuli which might bias their responses to the velocity test condition. The release compartment gate was operated from above and to the side to avoid frightening the fish by the motion of opening the gate, and wood panels were installed on each side of the compartment to shield the release compartment operator from the fish.

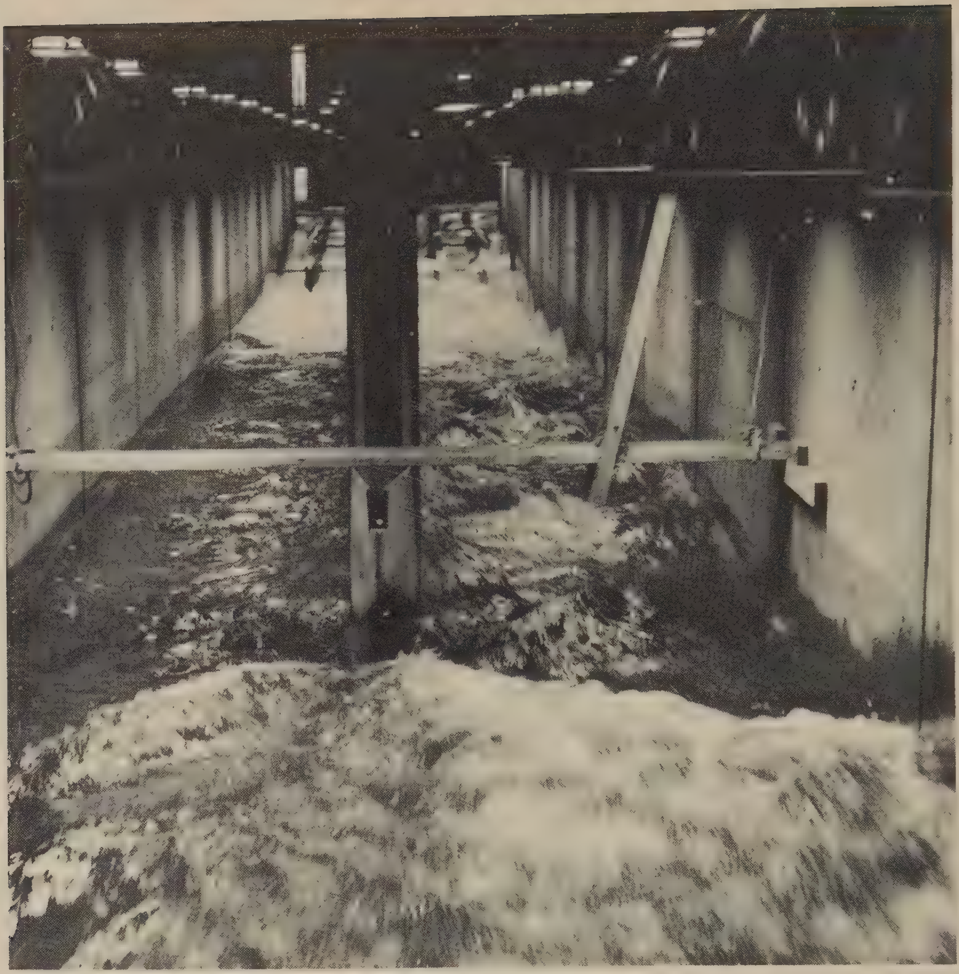


FIGURE 5.—View of choice area and channels showing 6 f.p.s. flow on left and 8 f.p.s. flow on right. Note positions of standing waves. Platform above downstream end of channels was used to check water velocities and was removed during the tests.

Lighting

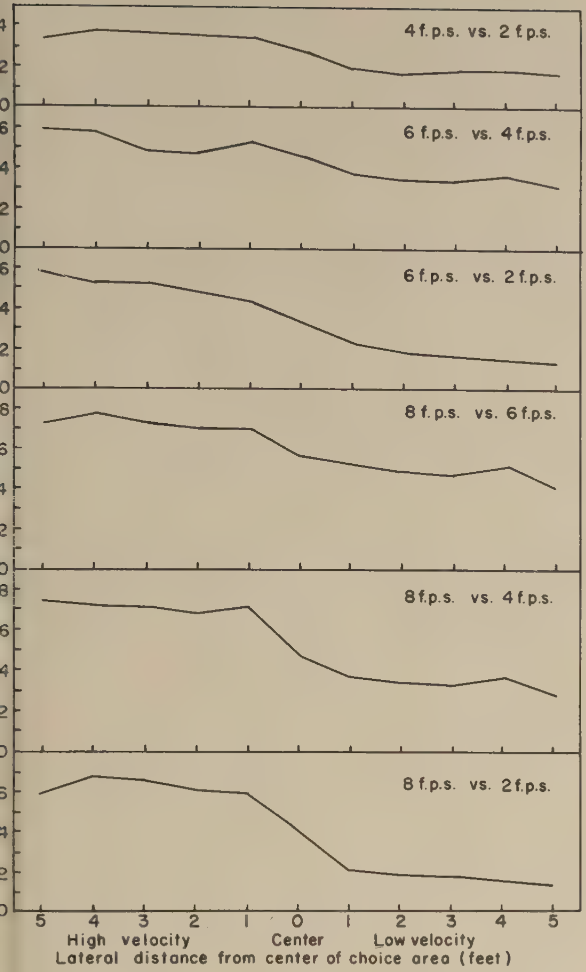
Uniform lighting was maintained within the channels and choice area by use of 1,000-watt mercury-vapor lamps mounted in polished reflectors. The lamps were suspended from horizontal wall brackets spaced 6 feet apart along the walls of the building and were adjusted to hang 8 feet above the level of the floor. This placed the lamps approximately 6 feet above the surface of the water (fig. 5).

Mean incident light intensities at the water surface in the choice area and within the channels were 604 foot-candles and 746 foot-candles, respectively. This light intensity was roughly comparable to that measured in daylight on a bright overcast day.

PROCEDURE

Experimental Design

The experiments were conducted in accordanc with a balanced 4 by 4 lattice-square design i five replicates (Cochran and Cox, 1950). Th high velocity for the 6 test conditions was alternated between north and south channels to provid a total of 12 different test treatments (table 2 section A). These, combined with the 4 contro treatments provided a total of 16 different treatments for each replicate. The rows and column of the design were randomized, and the treatment were assigned at random to the 16 treatmen numbers in each replicate (table 2, section B) The order of testing proceeded from replicate to V, and within each replicate from left to righ



URE 6.—Examples of velocity gradients occurring in cross section of choice area for each test condition.

TABLE 2.—*Outline of the 4 x 4 lattice-square design listing (A) the various test and control conditions and (B) the order of testing*

A. EXPERIMENTAL CONDITIONS (TREATMENTS)

Channel	Water velocity (feet per second)															
	Test conditions												Control conditions			
South	8	2	8	4	8	6	6	2	6	4	4	2	2	4	6	8
North	2	8	4	8	6	8	2	6	4	6	2	4	2	4	6	8

B. EXPERIMENTAL CONDITIONS (TREATMENTS) RANDOMLY FITTED TO BASIC LATTICE SQUARE DESIGN

Replicate	Treatments[1]			
I	1. S_8 N_6	2. S_2 N_8	3. S_8 N_2	4. S_4 N_4
	5. S_2 N_2	6. S_6 N_4	7. S_6 N_8	8. S_2 N_6
	9. S_6 N_2	10. S_6 N_6	11. S_8 N_4	12. S_4 N_2
	13. S_4 N_6	14. S_8 N_8	15. S_4 N_8	16. S_2 N_4
II	17. S_6 N_8	18. S_6 N_6	19. S_4 N_6	20. S_4 N_4
	21. S_8 N_6	22. S_2 N_4	23. S_8 N_4	24. S_6 N_4
	25. S_4 N_2	26. S_2 N_2	27. S_2 N_8	28. S_4 N_8
	29. S_8 N_8	30. S_8 N_2	31. S_2 N_6	32. S_6 N_2
III	33. S_4 N_6	34. S_8 N_4	35. S_2 N_8	36. S_2 N_6
	37. S_4 N_2	38. S_8 N_8	39. S_6 N_8	40. S_8 N_6
	41. S_6 N_4	42. S_4 N_4	43. S_6 N_2	44. S_4 N_8
	45. S_8 N_2	46. S_2 N_2	47. S_2 N_4	48. S_6 N_6
IV	49. S_8 N_8	50. S_8 N_4	51. S_2 N_2	52. S_4 N_4
	53. S_4 N_6	54. S_4 N_2	55. S_6 N_4	56. S_8 N_2
	57. S_4 N_8	58. S_6 N_6	59. S_2 N_6	60. S_8 N_6
	61. S_2 N_4	62. S_6 N_2	63. S_6 N_8	64. S_2 N_8
V	65. S_4 N_8	66. S_6 N_8	67. S_8 N_4	68. S_8 N_2
	69. S_4 N_2	70. S_4 N_4	71. S_2 N_4	72. S_2 N_6
	73. S_2 N_8	74. S_6 N_6	75. S_6 N_4	76. S_8 N_8
	77. S_2 N_2	78. S_4 N_6	79. S_8 N_6	80. S_6 N_2

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[1] Arabic numeral indicates order of testing, letter denotes channel, (S= south, N=north) and subscript denotes velocity (f.p.s.).

ng successive rows. The sample size for each t was set at 20 fish.

The original plan was to test both steelhead ut and chinook salmon simultaneously, conuing each test until the 20-fish sample of each cies had been obtained. It became apparent, vever, during several trial runs that chinook mon were not sufficiently abundant to meet se requirements. The replicated tests, there- , applied only to steelhead trout. Chinook mon were tested as they presented themselves ing the course of the experiments, but no effort made to maintain consistency in the sample s with regard to these species. A few silver mon were also tested during the course of the eriments.

To insure that the replicated tests would be as nogeneous as possible, the samples of 20 steelhead were restricted to fish estimated to be from 22 to 26 inches in length. Smaller and larger steelhead were tested when available; however, they were not included in the 20-fish samples.

Conduct of Experiments

In preparing for a given test, the predetermined stoplog arrangement was inserted at the upstream end of each channel and the water levels of the flow-introduction and collection pools were adjusted to the proper heights. A brief period was allowed for the flows to become stabilized, then water velocities were measured with a current meter at the downstream end of each channel (fig. 5).

After the velocities of each channel had been measured and the observers had taken their respective stations, the release compartment operator was signaled to start the test. The sliding gate on the picketed divider was raised, and a single fish was allowed to enter the compartment. After determining the species and estimating the length of the fish, the operator raised the sliding gate at the upstream end of the release compartment, allowing the fish to enter the choice area. An observer stationed on a walkway over the choice area followed the fish as it passed through the choice area and noted which channel was chosen. After the fish had passed through the channel a second fish was released and so on until the desired sample of 20 steelhead within the 22- to 26-inch size range had been tested.

Upon completion of a test, the main water supply entering the flow-introduction pool was shut off and the stoplog arrangement at the head of the channels was changed for the next test. The changeover could generally be accomplished within 15 minutes. However, usually several minutes elapsed before the fish would enter the release compartment after this change in hydraulic conditions.

During the course of the experiments every effort was made to keep the release technique and operation procedure as uniform as possible. The release compartment operator alternated his position in relation to the compartment after releasing each fish to minimize the chance of bias due to visual cues. If fish were noted in the upper reaches of the channels, tests were halted until these fish had moved on through the channel. This precaution was taken to ensure that the fish entering the choice area would not be affected by scent or visual perception of other fish in the channels. Rubber gloves were worn when changing the stoplogs at the head of channels to eliminate the chance of bias in response due to human scent.

An average of three to four tests were conducted each day, depending upon the availability of fish. Twenty-three days were required for the entire series of experiments.

RESULTS

A total of 80 individual tests were conducted: 60 involving a choice between a high and low velocity and 20 in which the velocities of the two flows were equal. Throughout the series of experiments a total of 2,064 steelhead trout (includes fish of all sizes), 750 chinook salmon, and 108 silver salmon were tested.

Response of Steelhead Trout

The analysis of the steelhead data was based upon the individual tests composed of 20 fish in the length range of 22 to 26 inches. The total sample consisted of 1,600 individuals, 1,200 in the test, and 400 in the control experiments. Th responses of these fish to the various individua control and test experiments are presented i tables 3 and 4. The data have been groupe according to experimental conditions to facilitat comparisons between individual trials and betwee test conditions.

The first step in the analysis of the data was t determine whether there were differences betwee the five replicates of the experimental desig (table 2). If not, the results of individual tes and control experiments could be combined t test for differences in response for the two channel in control tests, and differences in response for th different velocity combinations in test experiments

Since the high velocity of each test conditio occurred once in the north and once in the sout channel within each replicate, the percentage o fish choosing the north channel should be the sam for each replicate if the nature of the response di

TABLE 3.—*Percentage of steelhead choosing north and sout channels in each of the 20 control experiments*

[Samples consist of 20 fish ranging from 22–26 inches in length (estimated)

Replicate	Water velocity							
	2 f.p.s.		4 f.p.s.		6 f.p.s.		8 f.p.s.	
	North	South	North	South	North	South	North	South
I	40	60	60	40	30	70	55	4
II	30	70	70	30	65	35	65	3
III	55	45	50	50	50	50	75	2
IV	55	45	60	40	45	55	55	4
V	55	45	55	45	50	50	45	5
Mean	47	53	59	41	48	52	59	4

TABLE 4.—*Percentage of steelhead trout choosing high veloc- ity channel in each of the 60 test experiments*

[Each entry represents the response of 20 fish ranging from 22–26 inches f length (estimated)]

High velocity channel	Replicate	Test condition					
		8 f.p.s. vs. 2 f.p.s.	8 f.p.s. vs. 4 f.p.s.	8 f.p.s. vs. 6 f.p.s.	6 f.p.s. vs. 2 f.p.s.	6 f.p.s. vs. 4 f.p.s.	4 f.p.s. vs. 2 f.p.s.
North	I	75	65	65	70	60	6
	II	90	65	55	80	50	6
	III	90	55	25	60	60	8
	IV	80	50	60	75	60	6
	V	75	50	50	55	70	5
South	I	80	50	60	75	70	8
	II	80	50	50	65	75	7
	III	80	75	55	70	90	7
	IV	95	75	60	70	60	5
	V	90	75	35	90	40	6
Pooled percentage [1] to higher velocity.		83.5	61.0	51.5	71.0	63.5	68.

[1] Channels and replicates combined.

t differ between replicates. To test this hy-
thesis, data for each of the 80 trials given in
ble 2 were transformed to arcsin $\sqrt{\text{percentage}}$ to
rth channel and subject to an analysis of vari-
ce test. The results illustrate that the differ-
ces between replicates, columns, and rows were
t significant (table 5).

BLE 5.—*Analysis of variance for percentage of steelhead
hoosing north channel using the lattice-square design*

[Original percentages were transformed to arcsin $\sqrt{\text{percentage to north channel}}$]

Source	Sum of squares	Degrees of freedom	Mean square	F value
lications	139.498	4	34.87	.72 N.S.
atments	9025.443	15		
's (adjusted for treatments)	597.438	15		
's (adjusted for treatments d columns)	550.809	15	36.72	.76 N.S.
umns (adjusted for treat- ents)	1078.693	15		
umns (adjusted for treat- ents and rows)	1037.063	15	69.14	1.44 N.S.
or	1441.367	30	48.05	
Total	12235.809	79		

.S.—Not significant.

Response in control experiments.—Since no sig-
cant differences could be detected between the
e replicates of the lattice-square design, the four
trol tests for each replicate were combined and
jected to chi-square tests to determine whether
reference was demonstrated for either the north
south channel when the flows were of equal
ocity. The results of these tests show that the
parity between the observed response and the
ected 1:1 ratio was not great enough to indi-
e that a preference had been demonstrated for
her channel in any of the combined control
ts (table 6).

LE 6.—*Results of chi-square tests on number of steelhead
oosing the north and south channels in control tests at
ch velocity*

[Samples are composed of fish ranging from 22–26 inches in length]

Vater locity	Sam-ple size	Observed response		Expected response		Degree of freedom	Chi-square
		Chose north channel	Chose south channel	To north channel	To south channel		
'.p.s.							
	100	47	53	50	50	1	.36 N.S.
	100	59	41	50	50	1	3.24 N.S.
	100	48	52	50	50	1	.16 N.S.
	100	59	41	50	50	1	3.24 N.S.
Sum of chi-squares						4	7.00 N.S.

3.—Not significant, $p > .05$].

Response in test experiments

As no preference was shown for either the north or south channel in control tests and no significant differences between replicates were apparent, the data in table 4 (transformed to arcsin $\sqrt{\text{percentage}}$ to higher velocity) were subjected to a two-way analysis of variance to test the effects of channel and velocity differences in the 60 trials involving a choice between a high and low velocity. The results of the analysis of variance (table 7) illustrate that: (1) there were significant differences between the responses of the fish to the different test conditions, (2) these differences were independent of channel effects, i.e., they were evident when the higher velocity was in either the north or south channel and, (3) there was no preference indicated for either the north or south channels independent of velocity effects.

TABLE 7.—*Analysis of variance of the responses of steelhead trout to differences in water velocity for the six test conditions*

Variation due to—	Degrees of freedom	Mean square	Variance ratio
Differences between test conditions	5	482.958	**9.89
Differences between channels	1	156.558	3.21 N.S.
Interaction	5	6.937	.14 N.S.
Error	48	53.167	
Error (main effects)	53	48.805	

** Significant at .01 level.
N.S.—Not significant.

Although the preceding analysis of variance demonstrated that the responses for the higher velocity differed between test conditions, it does not reveal whether each test condition differed from all the rest or whether some were undifferentiated. A test devised by Tukey (Snedecor 1956) was employed in examining these differences. The results of the test demonstrate that the response for the higher velocity in the 8 vs. 2 f.p.s. choice condition was significantly greater than that exhibited in any of the other five test conditions, and the responses in the 6 vs. 2 and 4 vs. 2 f.p.s. test conditions were significantly greater than that in the 8 vs. 6 f.p.s. condition (table 8). Other differences were not significant. The mean percentages to the higher velocity listed in this table are transformed data and should not be confused with the actual percentages to the higher velocity given in table 4.

Table 8.—*Tests of differences between mean percentages of steelhead choosing the higher velocity*

[Data are arcsin $\sqrt{\text{percentage to higher velocity}}$]

Test condition		Mean percentage choosing higher velocity	Differences between mean percentages to higher velocity				
High velocity	Low velocity		$\overline{X}-$ 45.80	$\overline{X}-$ 51.53	$\overline{X}-$ 53.24	$\overline{X}-$ 55.89	$\overline{X}-$ 57.77
F.p.s.	*F.p.s.*	$\overline{X}$					
8	2	66.55	*20.75	*15.02	*13.31	*10.66	*8.78
6	2	57.77	*11.97	6.24	4.53	1.88	
4	2	55.89	*10.09	4.36	2.65		
6	4	53.24	7.44	1.71			
8	4	51.53	5.73				
8	6	45.80					

* Differences greater than 7.89 are significant at .05 level.

Since there were no significant differences between replicates and no preference (independent of the effects of velocity) was shown for either channel during control or test experiments, all trials of each test condition were combined to determine whether there was a significant response to the higher velocity. The results of chi-square tests performed on these data illustrate that the proportion of steelhead selecting the higher velocity is significantly greater than that choosing the low velocity in all except the 8 vs. 6 f.p.s. choice condition (table 9).

Table 9.—*Chi-square tests on results of choice experiments*

[Data are for steelhead estimated to be 22-26 inches in length.]

Test condition		Sample size	Observed response		Expected response		Chi-square
High velocity	Low velocity		Chose high velocity	Chose low velocity	To high velocity	To low velocity	
F.p.s.	*F.p.s.*	*Number of fish*	*Number of fish*	*Number of fish*			
8	2	200	167	33	100	100	**89.78
8	4	200	122	78	100	100	**9.68
8	6	200	103	97	100	100	.18 N.S.
6	2	200	142	58	100	100	**35.28
6	4	200	127	73	100	100	**14.58
4	2	200	136	64	100	100	**25.92

**Significant at .01 level.
N.S.—Not significant.

Table 10.—*Comparison between the responses of small (less than 25 inches) and large (25 inches and larger) steelhead for the high-velocity flow*

[Entries are percentage choosing high-velocity flow]

Length group	Test condition					
	8 f.p.s. vs. 2 f.p.s.	8 f.p.s. vs. 4 f.p.s.	8 f.p.s. vs. 6 f.p.s.	6 f.p.s. vs. 4 f.p.s.	6 f.p.s. vs. 2 f.p.s.	4 f.p.s. vs. 2 f.p.s.
Small	81	58	50	66	72	67
Large	75	62	56	59	75	68

Response in relation to fish size.—A thorough examination of the relationship between fish size and response was not possible as the steelhead tested during the course of the experiments were of nearly the same size, 80 percent ranging from 22 to 26 inches (fig. 7). Gross comparisons were made, however, by dividing all of the steelhead tested at each test condition into two size categories, small fish less than 25 inches and large fish 25 inches and greater in length, and comparing the percentages choosing the high velocity for each of the 6 test conditions (table 10). No significant differences could be detected between the percentage of small and large fish choosing the high velocity.

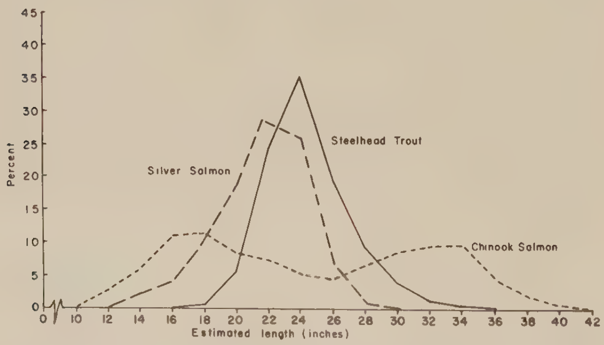


Figure 7.—Length composition of samples of steelhead trout, chinook salmon, and silver salmon tested in the velocity-preference experiments.

Response of Chinook Salmon

It has been stated that testing of chinook and silver salmon was considered as an incidental phase of the experiments, each test being terminated when the desired sample of steelhead trout had been tested. Samples of chinook salmon in individual tests ranged from 0 to 27 fish.

Control experiments.—In order to provide sample sizes large enough to test the hypothesis of random choice of channels in control experiments, it was necessary to combine the data for the four control tests (2 vs. 2, 4 vs. 4, 6 vs. 6, and 8 vs. 8 f.p.s.) within each replicate. Results of chi-square tests on these data demonstrate that a random choice of channels was exhibited when the flows were of equal velocity (table 11).

Test experiments.—As in control tests the data for individual experiments were combined in order to examine the response of chinook salmon to the various test conditions. Since there was a pronounced variation in the sizes of fish tested during the experiments it was appropriate to examine first the response in relation to fish size.

BLE 11.—*Response of chinook salmon to control tests for each of the five replicates*

ponses in each replicate represent grouped data for four individual tests.
i-square values test the hypothesis that equal numbers entered the two
annels]

plicate	Number of fish	Observed response		Expected response		Chi-square	Degrees of freedom
		Number of fish to—		Number of fish to—			
		North channel	South channel	North channel	South channel		
-------	25	11	14	12.5	12.5	0.36 N.S.	1
-------	34	19	15	17	17	.47 N.S.	1
-------	43	26	17	21.5	21.5	1.88 N.S.	1
-------	19	7	12	9.5	9.5	1.32 N.S.	1
-------	51	21	30	25.5	25.5	1.59 N.S.	1
ed-----	172	84	88	86	86	09 N.S.	1
of hi- ares--						5.62 N.S.	4
ro- ncity ffer- ce)----						5.53 N.S.	3

S.—Not significant.

e length frequency curve was bimodal and the
could be conveniently divided into two
eral size groups; one composed of fish less
n 25 inches and the other composed of fish
inches and greater in length (fig. 7). Chi-
are tests on these data indicate that there was
ignificant difference in the responses of small
large fish in only one out of the six test condi-
ns (table 12). In the 8 vs. 4 f.p.s. test a
nificantly greater proportion of large fish chose
higher velocity.

ince the response of large and small fish did
differ significantly in the majority of the tests,
s were combined to examine the group response
chinook to the different test conditions (table
Chi-square values illustrate that a signif-
tly greater proportion of chinook chose the
n velocity in all except the 6 vs. 8 f.p.s. test
condition. In this instance a larger proportion (not significant) of the fish chose the 6 f.p.s. velocity.

LE 12.—*Comparison between the responses of small (less an 25 inches) and large (25 inches and larger) chinook each test condition*

Test condition		Number of fish		Chose high velocity channel		Chi-square
gh velocity	Low velocity	Small	Large	Small	Large	
.p.s.	*F.p.s.*			*Percent*	*Percent*	
	2	37	63	91.9	93.6	0.09 N.S.
	4	38	42	52.6	80.9	**7.19
	6	35	31	45.7	45.2	.08 N.S.
	2	74	65	86.5	87.7	.70 N.S.
	4	42	27	57.1	70.4	1.24 N.S.
	2	64	60	71.9	75.0	.15 N.S.

gnificant difference between responses, p< .01.
.—Not significant.

TABLE 13.—*Chi-square tests on responses of chinook salmon to the higher velocity in the six different test conditions*

Test condition		Number of fish	Observed response		Expected response		Chi-square
High velocity	Low velocity		Chose high velocity	Chose low velocity	To high velocity	To low velocity	
F.p.s.	*F.p.s.*						
8	2	100	93	7	50	50	***73.96
8	4	80	54	26	40	40	**9.80
8	6	66	30	36	33	33	.54 N.S.
6	2	139	121	18	69.5	69.5	***76.32
6	4	69	43	26	34.5	34.5	*4.19
4	2	124	91	33	62	62	***27.13

N.S.—Not significant.
*Significant difference, p< .05.
**Significant difference, p<.01.
***Significant difference, p<.001.

Response of Silver Salmon

Comparatively few silver salmon were tested during the course of the experiments. The combined data in table 14 illustrate that silver salmon, like steelhead trout and chinook salmon, demonstrated a preference for the higher velocity in all except the 8 vs. 6 f.p.s. choice condition. Of the 18 fish tested during the control experiments, 8 chose the north channel and 10 chose the south channel.

TABLE 14.—*Velocity preference of silver salmon in six test conditions*

Water velocity		Number of fish	Chose high-velocity channel
High-velocity channel	Low-velocity channel		
F.p.s.	*F.p.s.*		*Percent*
8	2	12	83.3
8	4	14	85.7
8	6	13	46.1
6	2	24	83.3
6	4	22	68.2
4	2	5	100.0

Comparison Between Responses of Chinook Salmon and Steelhead Trout

Although a basic similarity in the response of steelhead trout and chinook salmon has been demonstrated, it is of interest to know whether the magnitude of the response varied between the two species. Chinook salmon demonstrated a stronger response for the higher velocity in four (8 vs. 2, 8 vs. 4, 6 vs. 2, and 4 vs. 2 f.p.s.) choice conditions (table 15). Chi-square values indicate that the response was significantly stronger in the 6 vs. 2 and 8 vs. 2 f.p.s. choice conditions. In the 8 vs. 6 and 6 vs. 4 f.p.s. choice conditions, steelhead trout demonstrated a stronger response for the higher velocity; however, chi-square values were not significant in either case. The data in table 15 include all steelhead trout and chinook salmon tested regardless of fish size.

TABLE 15.—*Comparison between the responses of steelhead trout and chinook salmon in the six test conditions*

[Chi-square values test the hypothesis that there was no difference in the response of the two species]

Test condition		Number of fish[1]		Chose high-velocity channel		Chi-square
High-velocity channel	Low-velocity channel	Steelhead trout	Chinook salmon	Steelhead trout	Chinook salmon	
F.p.s.	*F.p.s.*			*Percent*	*Percent*	
8	2	258	100	79.4	93.0	*9.47
8	4	249	80	59.0	67.5	1.55
8	6	266	66	52.2	45.4	.63
6	2	264	139	73.1	87.1	*10.86
6	4	257	69	63.8	62.3	..09
4	2	253	124	67.2	73.4	1.98

[1] Includes all sizes.

*Significant difference p<.01.

Response of Steelhead Trout and Chinook Salmon to a 12.9 vs. 2.7 f.p.s. Choice Condition

Upon completion of the high-velocity tests, exploratory experiments were conducted to examine the response of steelhead and chinook when presented with a choice between flows averaging 12.9 and 2.7 f.p.s. Velocities were measured at the downstream ends of the two channels. Average water depths were 1.8 feet in the 12.9 f.p.s. channel and 3.4 feet in the 2.7 f.p.s. channel. Water temperature remained a constant 66° F. during these tests.

The two channels and a portion of the introductory area are shown in figure 8. Fish were released individually into the introductory area by means of a release compartment mounted on the entrance tunnel (fig. 9). Experiments were conducted for only 2 days, September 18–19, and observations were made on 41 steelhead trout and 57 chinook salmon.

Results of these tests were quite similar to the preceding choice experiments, for both steelhead trout and chinook salmon demonstrated a preference for the higher velocity. Choosing the higher velocity were 75.6 and 89.5 percent, respectively. Of the 51 chinook entering the 12.9 f.p.s. velocity channel only 26 were able to swim the entire distance (85 feet) to the flow-introduction pool. The remaining 25 fish negotiated varying distances up the channels but were eventually swept back downstream to the introductory area. There was evidence that some of these fish even made second attempts at the high-velocity channel. Steelhead trout demonstrated a superior performance: 29 out of the 31 fish choosing the high velocity were able to negotiate the entire length of the channel.

HIGH-VELOCITY EXPERIMENTS

METHODS AND MATERIALS

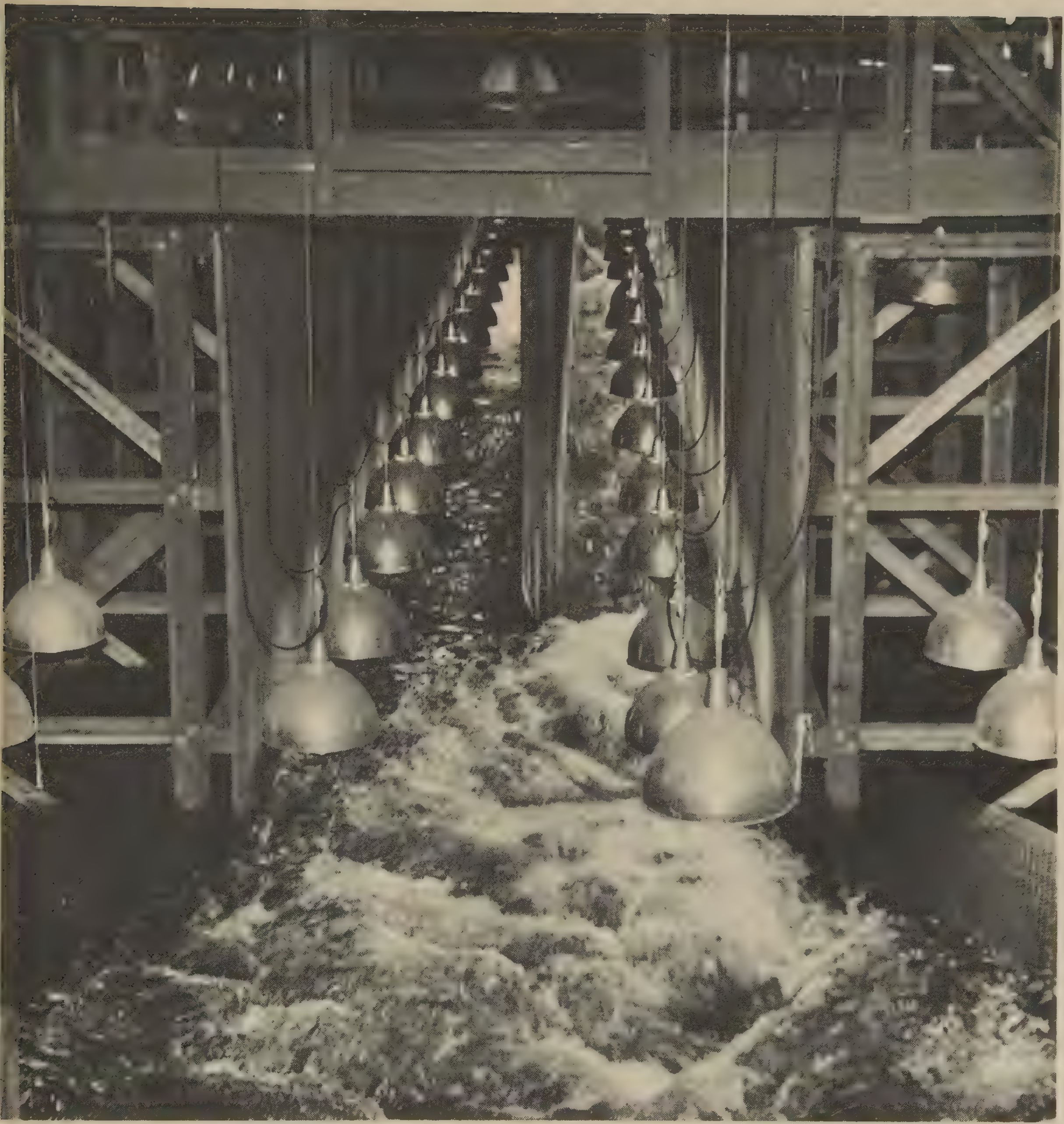
The method employed in measuring the performance or swimming ability of salmonids at relatively high velocities, like the choice experiments, relied entirely on the natural drives or instincts which motivate the fish to migrate upstream. These experiments differed from the choice experiments in that the migrating fish passing through the facility had no alternative but to pass through a channel carrying the test flow. The fish were permitted to enter the channel of their own volition, and if they failed to negotiate the entire channel and were swept back downstream they were allowed to remain in the introductory pool. Performance was measured by the distance which the fish could negotiate in the channel before becoming exhausted or discouraged. Velocities approximating 13 and 16 f.p.s. were tested. Tests were conducted during the period September 5–15. Water temperatures ranged from 66° to 67° F.

Experimental Area

The experimental area was modified for these experiments so that only the south channel was utilized (fig. 9). The north channel was blocked with stoplogs at the upstream end and screened at the downstream end to prevent fish from entering. Gray section markers painted on the channel floor at 5-foot intervals were used to measure the distance and fish were able to negotiate through the channel. Lighting was the same as was employed in the choice experiments.

Hydraulic Conditions

The two experimental flows were created by adjusting the slope of the channel floor and regulating the head (difference between the water level in flow-introduction pool and fish-intro-



IGURE 8.—View of two channels and introductory area during a choice experiment involving water velocities of 12.9 f.p.s. on the right and 2.7 f.p.s. on the left.

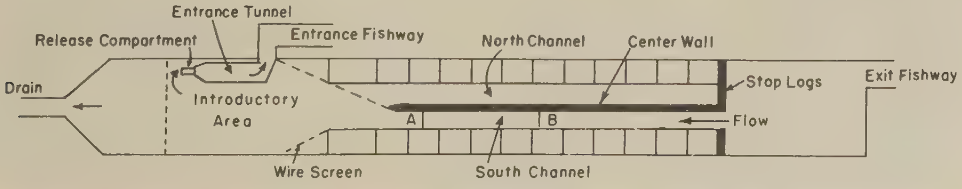

Entrance Tunnel
Release Compartment
Entrance Fishway
North Channel
Center Wall
Drain
Introductory Area
Stop Logs
Exit Fishway
A
B
Flow
Wire Screen
South Channel

FIGURE 9.—Sketch of laboratory showing experimental area modified for the high-velocity experiments.

ductory pool) on the channel. The total rise in floor level from the downstream end to the upstream end of the channel ranged from 1.4 feet at 13 f.p.s. to 2.5 feet at 16 f.p.s. The head on the channel ranged from 2.5 feet to 5.3 feet, respectively.

The mean water velocity and depth of flow for the two test conditions determined from rather extensive measurements in the first 35 feet of the channel before the experiments were begun, were 13.4 f.p.s. and 1.8 feet, and 15.8 f.p.s. and 1.8 feet, respectively. Velocities were measured with a current meter vertically at 4-inch intervals from the floor and horizontally at 1-foot intervals from the center of the channel at five different stations within the 35-foot reach. Examples of the distribution of velocities within the channel derived from these measurements are given in appendix figure 1 for each test condition. Velocities ranged from 11.8 to 14.4 f.p.s. in the 13.4 f.p.s. test condition and from 14.9 to 16.7 f.p.s. in the 15.8 f.p.s. test condition. The lowest velocities occurred near the floor next to the channel walls; the highest occurred just below the surface. During the course of the experiments velocities were checked only at the downstream end of the channel. Measurements at this point were made with a current meter at 1-foot intervals across the channel at 0.6 of the depth from the water surface.

With exception of the rather turbulent area at the upstream end, flows through the channel were nearly uniform for both test conditions. Although standing waves were created just below the channel entrance at both velocities, the

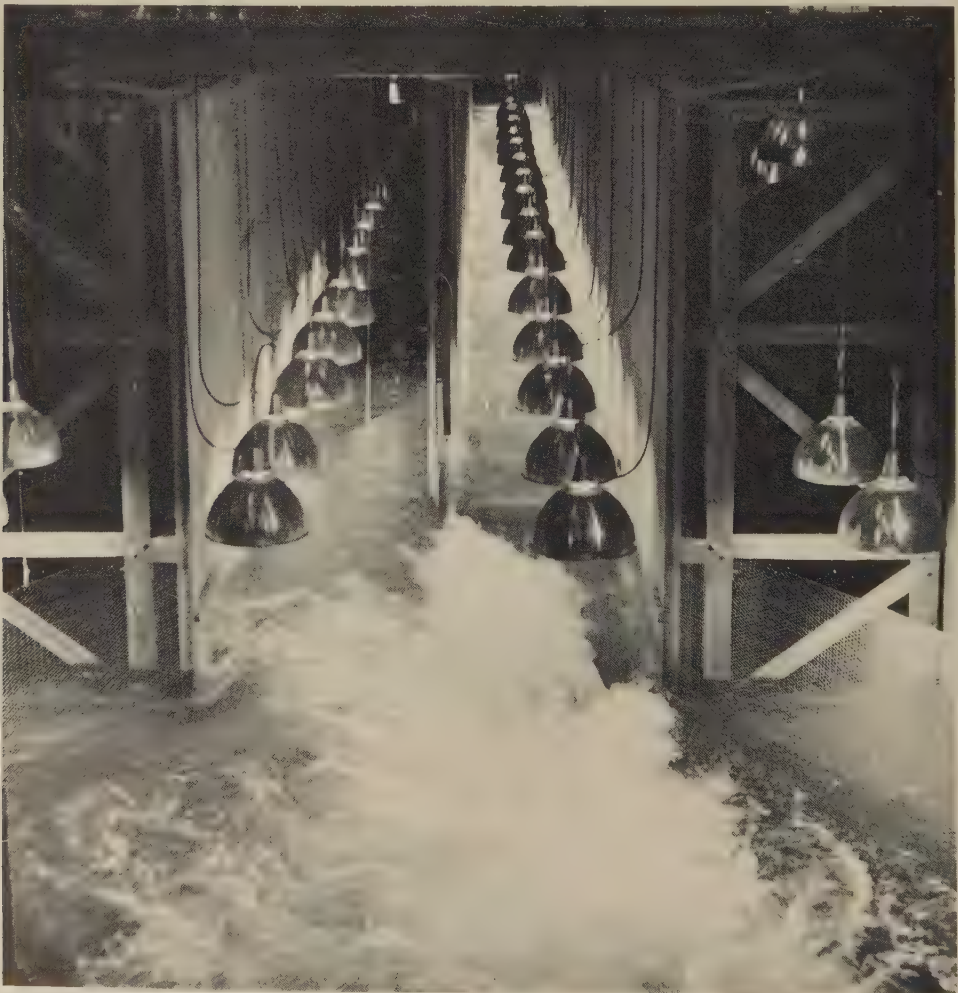


FIGURE 10.—View of south channel with 15.8 f.p.s. flow. A screen (barely visible) blocks entrance to north (left) channel.

sition of the wave and its effect on the flow in e approach area were quite different at the two locity levels. At 13.4 f.p.s. the wave was sitioned at the end of the hydrofoil and at ht angles to the channel flow (fig. 8). As a sult, the water velocity within the approach ea was greatly reduced. At 15.8 f.p.s. the nding wave extended diagonally across the trance to approximately the center of the annel. In this instance a high-velocity jet s created along the south wall of the approach ea (fig. 10). Velocities as high as 17.8 f.p.s. re measured at the end of the south wall. though the flow through the introductory area s turbulent at both velocities, there were areas ar both walls where fish could rest in relatively im water.

PROCEDURE

The fish utilized in these experiments were collected daily from the Washington Shore fishway. They swam into the entrance fishway channel (fig. 2) where they were held until tested. They were released individually by means of a release compartment mounted on the end of the entrance tunnel (fig. 11). Prior to release, the release compartment operator ascertained the species and estimated the length of each fish. Upon releasing the fish, he alerted an observer stationed on a walkway above the entrance to the test channel. When the fish entered the channel, this observer followed its movements from the walkway above the channel and noted the maximum distance which the fish attained.

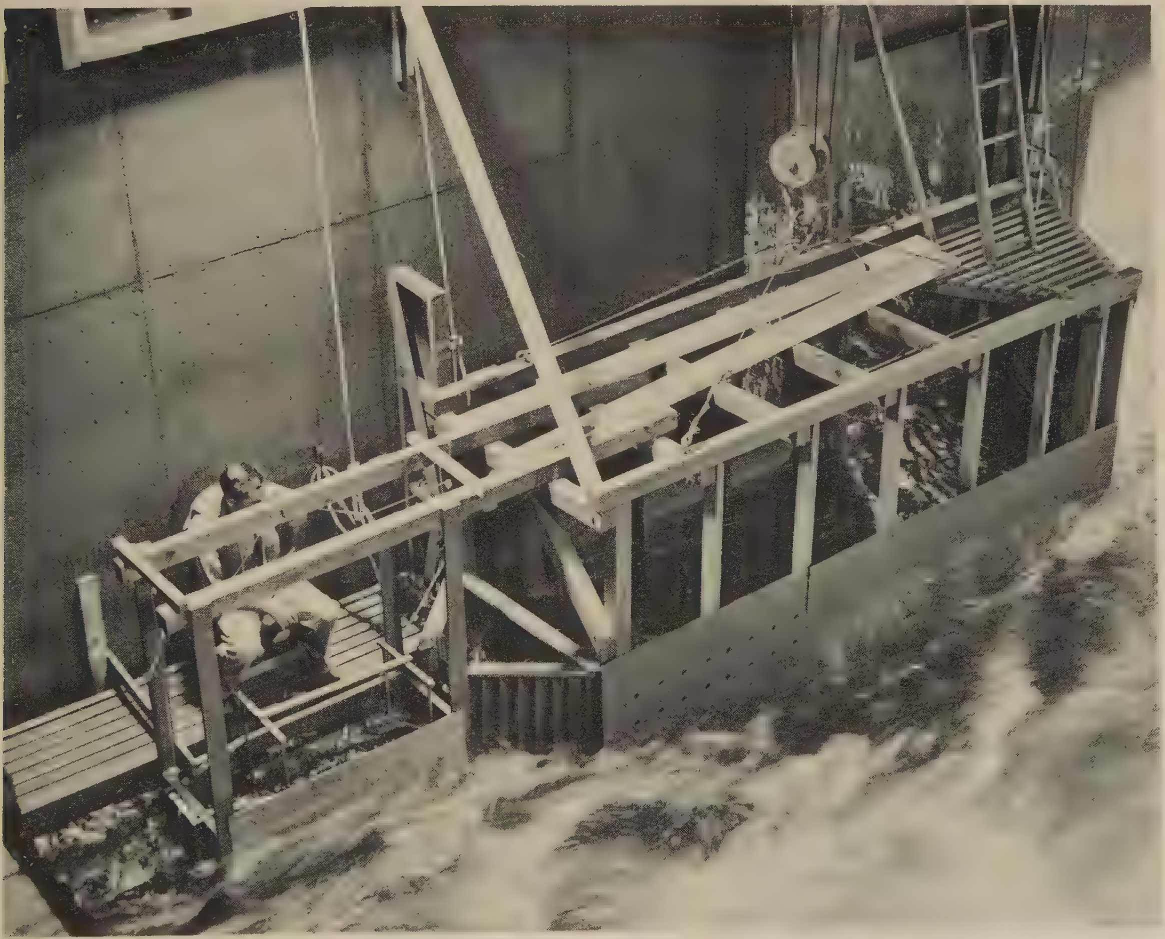


FIGURE 11.—View of entrance tunnel and release compartment utilized in the 13.4 and 15.8 f.p.s. velocity experiments.

Throughout the course of the experiments (especially in the 15.8 f.p.s. tests) fish that failed to pass through the channel and were swept back downstream often reentered and attempted to negotiate the channel again. Generally when this occurred, testing was merely delayed until the fish either passed through the channel or was again swept back downstream to the introductory area; the distance negotiated was recorded, and testing was resumed. If, however, these reentries became so numerous as to pose difficulty is distinguishing the fresh fish being introduced from the release compartment, the test was terminated or at least delayed until the fish could be cleared from the introductory area by reducing the channel velocity.

As many fish as possible were tested each day. The number varied from 30 to 60 fish depending upon availability. At the end of each day the channel velocity was reduced so that the fish which had accumulated in the introductory area could pass through the laboratory during the night.

RESULTS

The 13.4 f.p.s. velocity tests were conducted on September 5, 6, and 7, and the 15.8 f.p.s. tests were made on September 9, 10, 14, and 15. A total of 47 steelhead trout and 91 chinook salmon were tested in the 13.4 f.p.s. velocity flow, and 67 steelhead and 130 chinook, in the 15.8 f.p.s. flow.

A cursory examination of the data revealed that there was considerable variation in the swimming abilities of the fish tested in the two velocities. The distances attained by individual steelhead trout ranged from 10 to 85 feet (total length of channel) in the 13.4 f.p.s. velocity and from 14 to 85 feet in the 15.8 f.p.s. velocity. Chinook salmon ranged from 15 to 85 feet in the 13.4 f.p.s. velocity and from 0 feet (one fish failed to reach the channel entrance) to 85 feet in the 15.8 f.p.s.

The performances of the two species tested on different days are compared in table 16. The only consistent variation in performance between days occurred with the chinook tested in the 15.8 f.p.s. velocity. In this instance there was a decline in the median distance negotiated by the four groups of fish tested during the 7-day period. Since there were only slight differences in the mean lengths of the fish in the four tests, a real decline in the swimming ability of the chinook salmon tested during the 7-day period is indicated.

TABLE 16.—*Median distances attained by chinook salmon and steelhead trout tested on different days in velocities of 13.4 and 15.8 f.p.s.*

Velocity	Date	Number of fish		Mean length [1]		Median distance negotiated in 85-foot channel [2]	
		Chinook salmon	Steelhead trout	Chinook salmon	Steelhead trout	Chinook salmon	Steelhead trout
F.p.s.				*Inches*	*Inches*	*Feet*	*Feet*
13.4	Sept. 5	16	12	30.5	27.3	75	85
	Sept. 6	46	14	27.6	26.0	85	85
	Sept. 7	29	21	29.8	24.1	70	85
15.8	Sept. 9	44	13	27.3	25.1	30	74
	Sept. 10	40	25	27.4	26.1	28	85
	Sept. 14	21	9	26.0	24.0	21	79
	Sept. 15	25	20	26.6	24.9	19	76

[1] Based on estimated lengths.
[2] Values of 85 feet represent a minimum estimate of median as length of channel was only 85 feet.

The pooled data from the individual tests at each velocity are presented graphically to show the respective distances negotiated by the two species in the 85-foot channel (fig. 12). Each species has been divided into two general-size groups (small fish consisting of individuals estimated to be less than 25 inches in length and large fish consisting of individuals 25 inches and larger) to indicate the relationships between performance and fish size. These data clearly illustrate that

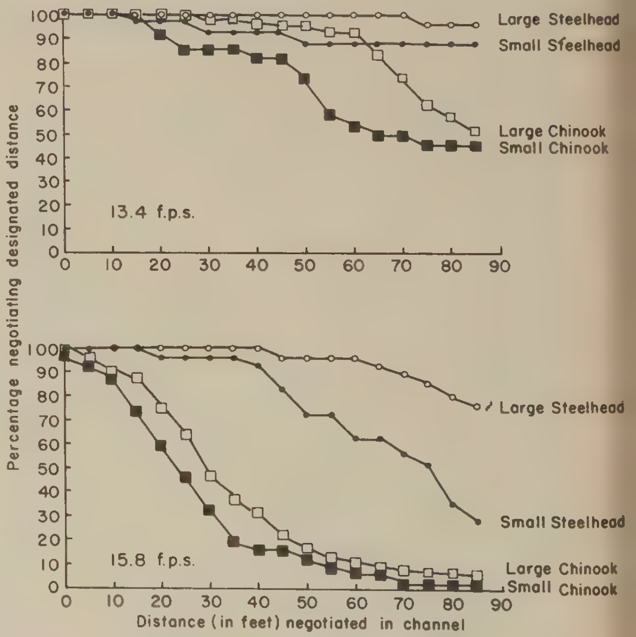


FIGURE 12.—Performances of small (estimated to be less than 25 inches in length) and large (25 inches and larger) steelhead trout and chinook salmon in velocities of 13.4 and 15.8 feet per second.

elhead trout were more successful than chinook
non in negotiating the two test flows and
ger fish of both species were more successful
n smaller fish. In the 13.4 f.p.s. tests 92 per-
t of the steelhead negotiated the entire 85-foot
nnel. In comparison, only 51 percent of the
iook salmon traveled this distance. The per-
nances of both species declined significantly in
15.8 f.p.s. velocity. Only 51 percent of the
elhead and 5 percent of the chinook negotiated
entire length of the channel. In comparing
performances of the two size groups it is
eresting to note that the decline in the perform-
e of steelhead between the 13.4 and 15.8 f.p.s.
ocity tests was due largely to the influence of
smaller fish. The proportion of large steelhead
otiating the entire 85-foot channel was reduced
only 20 percent while that of the smaller fish
reduced by 66 percent. In comparison, the
portions of large and small chinook salmon
otiating the channel were reduced by nearly
same proportion (90 and 95 percent, respec-
ly) between the 13.4 and 15.8 f.p.s. velocity
s.

n considering the performance curves in figure
we should bear in mind that: (1) the velocities
13.4 and 15.8 f.p.s. are mean values, (2) the
ances given apply only to measurements made
hin the confines of the channel and, (3) the
formance curves are based upon the distances
ined by the fish in their first attempt to
otiate the channel.

eference to appendix (fig. 1) illustrates that
may have encountered velocities somewhat
her or lower than 13.4 and 15.8 f.p.s. as they
ended the channel depending upon the course
y followed. Observations made during the
rse of the experiments indicated that although
e fish traversed back and forth across the
nnel they generally ascended the channel near
walls and were posited near the floor or at
t below middepth. The performance curves
figure 12, therefore, are probably associated
n velocities slightly lower than the mean values
en.

n the other hand the distances given in figure
ay be somewhat less than the actual distances
ch the fish negotiated in the two velocities,
ecially in the 15.8 f.p.s. tests. In these tests
flow was not dissipated upon entering the
roach area to the extent that it was in the
13.4 f.p.s. tests, and a high-velocity jet continued through the approach area to the introduction pool (fig. 10). A number of fish followed this jet as they approached the channel and were subjected to velocities of 15.8 f.p.s. or greater for distances up to 20 feet before entering the channel. The distances given in figure 12 apply only to the distance attained after entering the channel and may lead to an underestimation of the performance of the fish in this velocity.

It has been mentioned that fish which failed to negotiate the entire channel in their first attempt and were swept back downstream to the introductory area frequently reentered and attempted to negotiate the channel again. Although the mean distance negotiated by both steelhead trout and chinook salmon reentering the channel was slightly less than the mean distance achieved by the two species in their first attempts in both velocities, there was evidence that at least some of the fish were capable of achieving greater distances in the two velocities than they demonstrated in their first attempt. The maximum distances which all (100 percent) steelhead trout and chinook salmon were capable of negotiating in the two velocities may, therefore, be somewhat greater than is indicated in figure 12.

RATE OF MOVEMENT EXPERIMENTS

METHODS AND MATERIALS

These experiments were conducted concurrently with the choice and high-velocity experiments and utilized the same fish. Rates of movement were determined by simply recording the time required for the fish to pass through a 30-foot timing zone in the lower portion of the channels. Gray lines on the floor of the channels marked the boundaries of these zones. The downstream boundary or "start" line and the upstream or "finish" line are designated as points *A* and *B*, respectively, in figures 3 and 9.

Rates of movement in water velocities of 2, 4, 6, and 8 f.p.s. were measured during the velocity-preference experiments and in velocities of 13.4 and 15.8 f.p.s. during the high-velocity experiments. In the high-velocity experiments the upper end of the channel was not obstructed with the Denil ladder or stoplogs as it was in the choice experiments. It was possible, therefore, to obtain an additional measure of the rate of movement

TABLE 17.—*Distribution of times required by steelhead trout to negotiate the 30-foot timing zone in water velocities approximating 2, 4, 6, 8, 13, and 16 f.p.s.*

Time interval in seconds	Water velocity											
	2 f.p.s.		4 f.p.s.		6 f.p.s.		8 f.p.s.		13.4 f.p.s.		15.8 f.p.s.	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number [1]	Percent	Number [1]	Percent
0–0.9	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------
1.0–1.9	----------	----------	----------	----------	2	.3	1	.2	----------	----------	----------	----------
2.0–2.9	8	2.5	11	2.3	17	2.9	18	3.1	----------	----------	----------	----------
3.0–3.9	37	11.4	37	7.8	61	10.5	89	15.4	----------	----------	1	1.6
4.0–4.9	38	11.7	63	13.3	114	19.6	140	24.2	2	4.9	5	7.8
5.0–5.9	34	10.5	66	14.0	80	13.7	108	18.6	13	31.7	15	23.4
6.0–6.9	36	11.1	63	13.3	56	9.6	93	16.1	8	19.5	22	34.4
7.0–7.9	31	9.6	49	10.4	31	5.3	58	10.0	8	19.5	10	15.6
8.0–8.9	25	7.7	51	10.8	34	5.8	29	5.0	5	12.2	7	10.9
9.0–9.9	21	6.5	28	5.9	21	3.6	11	1.9	2	4.9	1	1.6
10.0–10.9	16	4.9	23	4.9	15	2.6	10	1.7	----------	----------	----------	----------
11.0–11.9	8	2.5	21	4.4	16	2.7	5	.8	3	7.3	1	1.6
12.0–12.9	12	3.7	17	3.6	13	2.2	----------	----------	----------	----------	2	3.1
13.0–13.9	7	2.2	6	1.3	8	1.4	1	.2	----------	----------	----------	----------
14.0–14.9	11	3.4	6	1.3	7	1.2	2	.3	----------	----------	----------	----------
15.0–15.9	11	3.4	5	1.1	6	1.0	1	.2	----------	----------	----------	----------
16.0–16.9	4	1.2	5	1.1	3	.5	1	.2	----------	----------	----------	----------
17.0–17.9	4	1.2	5	1.1	4	.7	----------	----------	----------	----------	----------	----------
18.0–18.9	2	.6	3	.6	3	.5	1	.2	----------	----------	----------	----------
19.0–19.9	4	1.2	3	.6	2	.3	1	.2	----------	----------	----------	----------
20.0–20.9	2	.6	----------	----------	3	.5	----------	----------	----------	----------	----------	----------
21.0–21.9	1	.3	1	.2	----------	----------	----------	----------	----------	----------	----------	----------
22.0–22.9	1	.3	1	.2	3	.5	1	.2	----------	----------	----------	----------
23.0–23.9	2	.6	----------	----------	1	.2	----------	----------	----------	----------	----------	----------
24.0–24.9	----------	----------	1	.2	1	.2	----------	----------	----------	----------	----------	----------
25.0–25.9	----------	----------	----------	----------	----------	----------	1	.2	----------	----------	----------	----------
26.0–26.9	----------	----------	2	.4	2	.3	----------	----------	----------	----------	----------	----------
27.0–27.9	3	.9	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------
28.0–28.9	----------	----------	----------	----------	1	.2	----------	----------	----------	----------	----------	----------
29.0–29.9	1	.3	2	.4	----------	----------	----------	----------	----------	----------	----------	----------
30.0+	5	1.5	3	.6	79	13.6	8	1.4	----------	----------	----------	----------
Total number of fish	324	----------	472	----------	583	----------	579	----------	41	----------	64	----------

[1] Represents only fish which were able to negotiate timing zone.

(from point B to the upstream end of the channel) for those fish which negotiated the entire length of the channel.

PROCEDURE

Fish were timed through the 30-foot zone with stopwatches by an observer stationed on the catwalk above the entrances of the channels. During the choice experiments a single watch was used. It was started as the fish crossed point *A* and stopped when the fish crossed point *B*.

During the high-velocity studies two watches were employed. One was used as above to record the time required to negotiate the 30-foot zone. The second watch was started as the fish crossed point *B* at the end of the 30-foot zone and stopped when the fish reached the upstream end of the channel. If the fish failed to negotiate the entire channel, the watch was stopped when the fish started to fall back downstream.

RESULTS

The distributions of individual times required by steelhead trout, chinook, and silver salmon to negotiate the 30-foot timing zone in the various water velocities tested are given in tables 17, 18, and 19. Passage times listed for velocities from 2 to 8 f.p.s. were measured during the choice experiments and include all fish tested at a given velocity regardless of choice condition. Passage times listed for water velocities of 13.4 and 15.8 f.p.s. were measured during the high-velocity experiments and include only those fish which were able to negotiate the timing zone.

Relationship Between Water Velocity and Rate of Movement by Species

Since the passage times do not conform to a normal type distribution in all instances, a nonparametric method was considered appropriate in comparing passage times between species and water velocities. The median passage time with 95-percent confidence limits was selected as the test statistic. These values for each species and velocity are presented in table 20. Rates of movement in each velocity, calculated by dividing the length of the timing zone (30 feet) by the median times in table 20, are compared in figure 13. Rates of movement ranged from 3.1 to 6.9 f.p.s., varying with species and water velocity.

A comparison of median times in table 20 reveals the following with respect to differences between

LE 18.—*Distribution of times required by chinook salmon to negotiate the 30-foot timing zone in water velocities approximating 2, 4, 6, 8, 13, and 16 f.p.s.*

ne interval in seconds	Water velocity											
	2 f.p.s.		4 f.p.s.		6 f.p.s.		8 f.p.s.		13.4 f.p.s.		15.8 f.p.s.	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number [1]	Percent	Number [1]	Percent
----	----	----	----	----	----	----	----	----	----	----	----	----
9	1	1.1	----	----	----	----	----	----	----	----	----	----
9	14	15.2	20	10.9	20	9.1	7	3.5	----	----	----	----
9	24	26.1	41	22.4	35	16.0	19	9.6	----	----	----	----
9	18	19.6	39	21.3	44	20.1	41	20.7	----	----	1	2.6
9	14	15.2	25	13.7	57	26.0	50	25.2	2	2.3	4	10.2
9	7	7.6	19	10.4	14	6.4	37	18.7	9	10.7	4	10.2
9	3	3.3	10	5.5	14	6.4	18	9.1	17	20.2	10	25.6
9	5	5.4	4	2.2	7	3.2	14	7.1	23	27.4	9	23.1
9	2	2.2	6	3.3	5	2.3	5	2.5	21	25.0	6	15.4
0.9	3	3.3	7	3.8	5	2.3	1	.5	10	11.9	4	10.2
1.9	----	----	4	2.2	2	.9	3	1.5	1	1.2	1	2.6
2.9	----	----	1	.5	----	----	1	.5	----	----	----	----
3.9	----	----	2	1.1	----	----	----	----	1	1.2	----	----
4.9	1	1.1	----	----	2	.9	----	----	----	----	----	----
5.9	----	----	3	1.6	----	----	1	.5	----	----	----	----
6.9	----	----	----	----	----	----	----	----	----	----	----	----
7.9	----	----	----	----	2	.9	----	----	----	----	----	----
8.9	----	----	----	----	1	.5	1	.5	----	----	----	----
9.9	----	----	----	----	1	.5	----	----	----	----	----	----
0.9	----	----	1	.5	----	----	----	----	----	----	----	----
1.9	----	----	----	----	----	----	----	----	----	----	----	----
2.9	----	----	----	----	2	.9	----	----	----	----	----	----
3.9	----	----	----	----	1	.5	----	----	----	----	----	----
4.9	----	----	----	----	2	.9	----	----	----	----	----	----
5.9	----	----	----	----	----	----	----	----	----	----	----	----
6.9	----	----	1	.5	----	----	----	----	----	----	----	----
7.9	----	----	----	----	----	----	----	----	----	----	----	----
8.9	----	----	----	----	1	.5	----	----	----	----	----	----
9.9	----	----	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	4	1.8	----	----	----	----	----	----
Total number of fish	92	----	183	----	219	----	198	----	84	----	39	----

epresents only fish which were able to negotiate timing zone.

LE 19.—*Distribution of times required by silver salmon negotiate the 30-foot timing zone in water velocities pproximating 2, 4, 6, and 8 f.p.s.*

ime interval in seconds	Water velocity							
	2 f.p.s.		4 f.p.s.		6 f.p.s.		8 f.p.s.	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
----	----	----	----	----	----	----	----	----
9	----	----	----	----	----	----	----	----
9	----	----	----	----	1	2.6	----	----
9	----	----	----	----	2	5.3	1	3.1
9	1	11.1	2	12.5	3	7.9	6	18.7
9	1	11.1	5	31.3	4	10.5	11	34.4
9	----	----	1	6.2	7	18.4	5	15.6
9	1	11.1	2	12.5	4	10.5	7	21.9
9	1	11.1	----	----	6	15.8	1	3.1
9	1	11.1	----	----	----	----	1	3.1
0.9	1	11.1	2	12.5	1	2.6	----	----
1.9	----	----	1	6.2	1	2.6	----	----
2.9	----	----	1	6.2	1	2.6	----	----
3.9	1	11.1	----	----	----	----	----	----
4.9	----	----	----	----	1	2.6	----	----
5.9	----	----	----	----	----	----	----	----
6.9	----	----	----	----	----	----	----	----
7.9	----	----	----	----	----	----	----	----
8.9	----	----	----	----	----	----	----	----
9.9	1	11.1	----	----	----	----	----	----
0.9	----	----	----	----	1	2.6	----	----
1.9	----	----	----	----	1	2.6	----	----
2.9	----	----	----	----	----	----	----	----
3.9	----	----	----	----	----	----	----	----
4.9	----	----	----	----	1	2.6	----	----
5.9	----	----	----	----	----	----	----	----
6.9	----	----	----	----	----	----	----	----
7.9	----	----	----	----	----	----	----	----
8.9	----	----	1	6.2	----	----	----	----
9.9	----	----	----	----	----	----	----	----
----	1	11.1	1	6.2	4	10.5	----	----
otal number of fish	9	----	16	----	38	----	32	----

species: (1) chinook salmon moved significantly faster (required less time to negotiate the 30-foot timing zone) than steelhead trout or silver salmon in velocities of 2, 4, and 6 f.p.s., (2) the rates of movement of the three species were approximately equal at 8 f.p.s., and (3) chinook salmon were

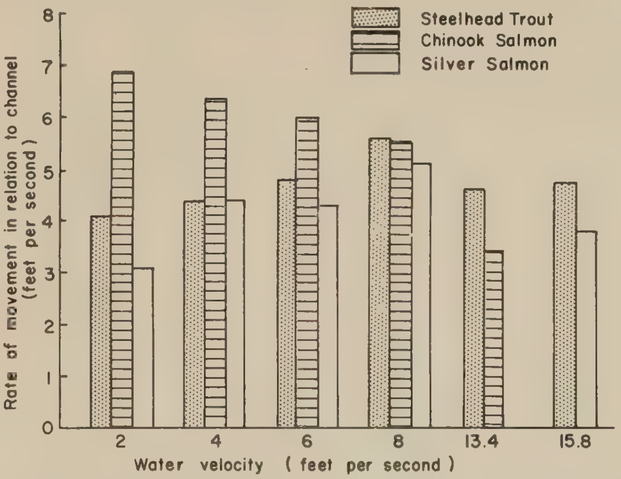


FIGURE 13.—Average rates of movement maintained through the 30-foot timing zone by steelhead trout, chinook salmon, and silver salmon in the six velocities tested. Rates are based on the median time required to negotiate the timing zone.

TABLE 20.—*Median passage times of steelhead trout, chinook and silver salmon through the 30-foot timing zone in water velocities approximating 2, 4, 6, 8, 13, and 16 f.p.s.*

Species	Median and [1] 95% confidence limits	Passage time in seconds						Sample size					
		Water velocity (f.p.s.)						Water velocity (f.p.s.)					
		2	4	6	8	13.4	15.8	2	4	6	8	13.4	15.8
Steelhead trout	Lower limit	6.6	6.4	5.7	5.0	5.8	5.9						
	Median	7.4	6.8	6.2	5.4	6.5	6.3	324	472	583	579	41	64
	Upper limit	8.0	7.5	6.7	5.6	7.6	6.9						
Chinook salmon	Lower limit	3.7	4.2	4.6	5.1	8.0	7.0						
	Median	4.3	4.7	5.0	5.5	8.7	8.0	92	183	219	198	84	39
	Upper limit	5.2	5.5	5.3	6.0	9.0	8.9						
Silver salmon	Lower limit	5.8	5.4	6.4	5.4	--------	--------						
	Median	9.7	6.8	7.0	5.8	--------	--------	9	16	38	32	0	0
	Upper limit	19.2	11.0	8.3	6.9	--------	--------						

[1] If the median passage time listed for a given species and velocity does not lie between the lower and upper limits listed for another velocity or species, the two passage times are considered to be significantly different.

significantly slower than steelhead trout in water velocities of 13.4 and 15.8 f.p.s.

Definite trends are noted when rates of movement and water velocities are compared (fig. 13). Steelhead moved progressively faster as the water velocity increased from 2 to 8 f.p.s.; then slowed down somewhat in velocities of 13.4 and 15.8 f.p.s. The rate of movement at 8 f.p.s. was significantly faster than at any other velocity (table 20). Silver salmon, although slightly slower than steelhead, also moved faster as the water velocity increased from 2 to 8 f.p.s. Chinook salmon differed from steelhead trout and silver salmon in that their rate of movement decreased with an increase in water velocity; the fastest rate of movement being achieved in the 2 f.p.s. velocity.

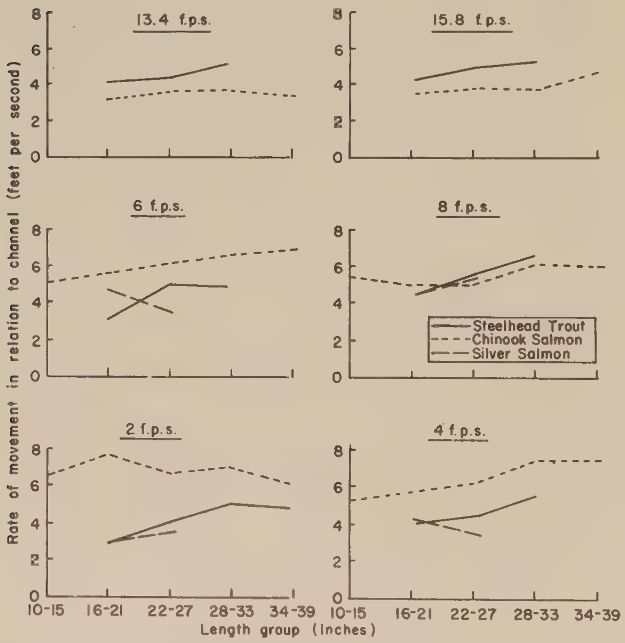


FIGURE 14.—Relationship between fish size and rate of movement. Rates are based on the median passage time of each length group. Lengths of individual fish were estimated. Underscored headings represent water velocities.

Examination of the relationship between fish size and rate of movement illustrates the differences previously noted in the rate of movement between species cannot be attributed to differences in size of the fish (fig. 14). Comparisons of the rates of movement between species by length groups agrees closely with the trends noted in figure 13. A direct relationship between size and rate of movement is also indicated. Steelhead were consistent in this respect throughout the various velocities tested. With the exception of the fish tested at 2 f.p.s., chinook demonstrated a similar consistency. Silver salmon were not as consistent. At 2 and 8 f.p.s. the larger fish move fastest, while at velocities of 4 and 6 f.p.s. the smaller fish moved fastest. It should be noted, however, that the silver salmon data represent comparatively small sample sizes and thus may not be reliable.

Maximum Observed Swimming Speeds

The preceding rates of movement were base upon the speed of the fish in relation to the channel and did not take into account the wate velocity in which they were measured. Swimming speeds may be calculated by adding the velocity of the flow to these rates of movement.

Maximum observed swimming speeds for steelhead trout, chinook, and silver salmon at eac velocity are given in table 21. The fastest fis timed was a 24-inch steelhead which maintaine average swimming speed of 26.8 f.p.s. while ssing through the 30-foot timing zone. Maxi- im observed swimming speeds for chinook and ver salmon were 21.9 and 17.5 f.p.s. respectively. Here again the water velocities given are mean lues and may be somewhat lower or higher than actual velocities which the fish encountered pending upon the course they followed ascend- the channel (appendix fig. 1). The maximum imming speeds based on these values, therefore, subject to an unknown degree of error depend- upon the distribution of velocities within the annel and the course the fish followed.

BLE 21.—*Maximum observed swimming speeds of steel- ead trout, chinook, and silver salmon timed through the 0-foot timing zone in water velocities ranging from 2 to 5.8 f.p.s.*

Species	Water velocity	Water temperature	Estimated length	Rate of movement through timing zone	Swimming speed [1]	
	F.p.s.	*° F*	*Inches*	*F.p.s.*	*F.p.s.*	*M.p.h.*
head trout	2.0	66.5	24	12.0	14.0	9.5
	4.0	66.5	28	13.6	17.6	12.0
	6.0	66.5	30	18.7	24.7	16.8
	8.1	66.5	24	18.7	26.8	18.3
	13.4	67.0	32	6.5	19.9	13.6
	15.8	66.5	24	7.7	23.5	16.0
ook salmon	2.0	66.0	20	15.8	17.8	12.1
	3.9	66.5	28	14.3	18.2	12.4
	5.9	66.0	32	14.3	20.2	13.8
	7.9	65.5	32	13.6	21.5	14.7
	13.4	67.0	28	5.8	19.2	13.1
	15.8	67.0	38	6.1	21.9	14.9
r salmon	2.1	66.0	18	7.3	9.4	6.4
	3.9	66.0	14	7.0	10.9	7.4
	5.9	66.5	24	11.5	17.4	11.9
	8.4	66.5	24	9.1	17.5	11.9

wimming speed equals rate of movement maintained through 30-foot ig zone plus the velocity of flow in which the rate was measured.

er Factors Related to Rate of Movement

Effect of nonuniform flow upon rate of move- t.—At a water velocity of 6 f.p.s. a standing ve was created in the channel. Although the ition of the wave varied somewhat in relation he channel during the different test conditions, vas generally posited within the limits of the ing zone. During the course of the experi- nts it became apparent that this wave was cting the rate at which fish swam through the ing zone. Some of the fish would stop when y reached the wave and remain for periods ging from a few seconds to several minutes. s accounts for the comparatively greater per- tages of steelhead, chinook, and silver salmon uiring 30 seconds or more to negotiate the ing zone in the 6 f.p.s. velocity tests. A com- son of the distributions of passage times in tables 17, 18, and 19 indicates that the occurrence of the wave affected steelhead trout and silver salmon more than it did chinook salmon; 13.6 percent of the steelhead trout and 10.5 percent of the silver salmon required 30 seconds or longer to negotiate the timing zone in contrast to 1.8 percent of the chinook salmon.

Relationship between swimming ability and rate of movement.—Data on samples of fish tested at water velocities of 13.4 and 15.8 f.p.s. were examined to determine whether there were significant differences in time required to negotiate the timing zone between fish which were able to negotiate the entire channel and those that failed to do so. The distribution of sample sizes restricted the comparisons to chinook salmon at 13.4 f.p.s. and steelhead trout at 15.8 f.p.s. Passage times were obtained for only three steelhead trout which failed to negotiate the channel at 13.4 f.p.s. velocity and for only six chinook salmon which were able to negotiate the entire channel at 15.8 f.p.s. The limited data indicate that the ability of the fish to negotiate the channel was not reflected in the passage time through the timing zone (table 22).

The data for steelhead trout and chinook salmon which were able to negotiate the entire channel in the 13.4 and 15.8 f.p.s. tests were further examined to determine whether the rates of movement decreased as the fish ascended the channel. A comparison was made of rates of movement measured through the first 30 feet of the channel and those measured through the next 50 feet of the channel (table 23). By inspection, no decrease in the rate

TABLE 22.—*Differences between mean passage times of fish which negotiated entire channel and those which failed to do so*

[Data are for chinook in 13.4 f.p.s. velocity and steelhead in 15.8 f.p.s. velocity]

Water velocity	Species	Size [1] group	Mean time required to negotiate 30-foot timing zone		Difference (B−A)	Sample size	
			A Negotiated entire channel	B Failed to negotiate entire channel		A	B
F.p.s.			*Seconds*	*Seconds*	*Seconds*		
13.4	Chinook salmon.	small	9.03	9.14	+.11 N.S.	7	12
		large	8.48	8.31	−.17 N.S.	32	33
15.8	Steelhead trout.	small	7.29	6.84	−.45 N.S.	10	25
		large	5.95	7.36	+1.41 N.S.	22	7

[1] Small fish consist of individuals 24 inches and less in length, large fish consist of individuals 25 inches and greater in length.
N.S.—Not significant.

TABLE 23.—*Comparison of steelhead and chinook rates of passage through the lower and upper sections of the channel in water velocities of 13.4 and 15.8 f.p.s.*

Water velocity	Species	Size group	Sample size	Mean rate of movement through	
				First 30 feet	Next 50 feet
F.p.s.				*F.p.s.*	*F.p.s.*
13.4	Steelhead trout	small	15	4.0	3.8
		large	21	4.7	4.7
	Chinook salmon	small	6	3.2	3.3
		large	31	3.5	3.6
15.8	Steelhead trout	small	7	4.4	3.3
		large	20	5.0	4.0
	Chinook salmon	small	--------	--------	--------
		large	4	5.2	4.6

of movement is apparent among either steelhead trout or chinook salmon at 13.4 f.p.s. At 15.8 f.p.s. both steelhead and chinook showed a declining rate of movement as they ascended the channel.

DISCUSSION AND CONCLUSIONS

The results of the preceding experiments clearly demonstrate that water velocity is an important consideration in the design and operation of fishways.

The general response for the high-velocity flow in the choice experiments emphasizes the importance of maintaining adequate attraction flows at fishway entrances. The variation in the response for a given flow velocity among the different experimental conditions suggests that the relative attractiveness of a fishway entrance may vary with the magnitude of the flows adjacent to the entrance, and if these contrasting flows are strong enough, a significant proportion of the fish approaching the fishway might be diverted from the entrance. This may be especially true at low head dams on the Columbia River where entrance flows must often compete with comparatively strong spillway or turbine discharges. The results of the two exploratory tests involving a choice between velocities of 2.7 and 12.9 indicate that at least some fish might repeatedly enter and attempt to negotiate velocities beyond their swimming ability even though a low-velocity passage was near at hand.

Admittedly the responses demonstrated in the laboratory may not be directly applicable to conditions normally existing at fishway entrances. The interaction of other factors such as turbulence; turbidity; differences in water quality, tempe ture, or light intensity; and possibly tendency the fish to follow the shoreline might influe the response to flow differences in the vicinity fishway entrances. We have no assurance, the fore, that the relative attractiveness of a fishw could be greatly improved by striving to maint the entrance velocity at a higher level than ad cent flows from spillway or turbine discharg Furthermore, since the high-velocity channel these experiments always carried a proportiona greater quantity of water, we have not definit established that the fish were responding solely velocity differences. Additional studies should conducted to determine the relative importance flows in attracting adult salmonids.

The results of the high-velocity experime demonstrate that the maximum water veloc which may be employed at the entrance or wit a fishway will be governed by the species and s of fish involved and the distance which the are required to negotiate. When a fishway designed to pass several species simultaneously maximum allowable velocities should be det mined by the swimming ability of the weak species. It is evident that velocities of 13 and feet per second could not be utilized in passa facilities designed for both steelhead trout a chinook salmon unless relatively short distan are involved (fig. 12). From the performan of the two species in the choice experiments would conclude that the maximum velocity wh could be employed for distances of approximat 85 feet would lie somewhere between 8 and 13 f. It is recognized that determination of a maxim velocity which may be safely utilized in passa facilities must not rely solely on the demonstra ability of the fish to negotiate a required distan The latent effects of the strenuous effort which m be required to negotiate the passage must also considered. Paulik, DeLacy, and Stacy (19 have demonstrated that salmonids may requir period of several hours to recover from exhaust swimming efforts, and Black (1958) has discus the possible lethal effects and reduction of sw ming ability brought about by sustained sev muscular exertion.

The recent findings of Paulik and DeLacy (19 indicating that the swimming ability of ad salmonids may vary as the fish proceed up river suggest that caution must be exercised

lying the results of the Bonneville experiments
situations farther up the river.

he results of the rate of movement experiments
nonstrate that certain water velocities may be
re conducive to passing fish through channels
n others. The differences in the rate of move-
nt between species in these experiments pre-
le a definite decision as to which velocity would
most effective in passing these fish through
nnels. Chinook salmon demonstrated the fast-
rate of movement in the 2 f.p.s. velocity while
lhead trout and silver salmon moved fastest
the 8 f.p.s. velocity. Perhaps the present
ndard (Bureau of Commercial Fisheries, 1958)
f.p.s. is adequate when dealing with the species
ized in these experiments. This velocity
ears strong enough to keep the fish orientated
moving through the channel at a satisfactory
and would certainly require the least effort of
various velocities tested. It is significant to
e, however, that our observations were made
a shallow, well-lighted, relatively narrow
nnel; somewhat different patterns of move-
nt might be demonstrated in deeper, wider,
often darker passage channels frequently
ountered at dams.

he fact that some fish were observed to hesitate
he standing wave created by the 6 f.p.s. ve-
ty suggests a laminar-type flow might be more
ducive to a uniform rate of passage through
nnels.

SUMMARY

he purpose of these experiments was to ex-
ne the influence of water velocity upon the
entation, performance, and rate of movement
adult migrating salmonids of the Columbia
er. Experiments were conducted at the Fish-
s-Engineering Research Laboratory, Bonne-
e Dam, during the months of August and
tember 1957. Steelhead trout and chinook
non were the principal species involved in
se experiments. A few silver salmon were
tested. The various experiments which
e conducted and their results are outlined
ow.

city-preference experiments

he orientative influence of water velocity was
mined by offering the fish a choice of two
nnels carrying flows of different velocities.
following six velocity combinations were
tested: 8 vs. 2, 8 vs. 4, 8 vs. 6, 6 vs. 2, 6 vs. 4, and 4 vs. 2 feet per second. The response for the high or low velocity in each test condition was measured by the number of fish selecting each channel. The responses of 2,064 steelhead trout, 750 chinook salmon, and 108 silver salmon were observed during the period August 8–30. The following results were obtained:

1. The percentages of steelhead choosing the high-velocity channel in order of the choice conditions listed above were 79.4, 59.0, 52.2, 73.1, 63.8, and 67.2, respectively. This preference for the high velocity was statistically significant for all except the 8 vs. 6 f.p.s. choice condition.

2. The percentages of chinook choosing the high-velocity channel for the above choice conditions were 93.0, 67.5, 45.4, 87.1, 62.3, and 73.4, respectively. Again, as in the case of steelhead, the preference for the higher velocity was statistically significant for all except the 8 vs. 6 f.p.s. choice condition. Chinook demonstrated a more positive response than steelhead for the high velocity in four (8 vs. 2, 8 vs. 4, 6 vs. 2, and 4 vs. 2 f.p.s.) out of the six test conditions. The response was significantly greater at 8 vs. 2, and 6 vs. 2 f.p.s. No significant difference could be demonstrated between the response of large (25 inches and larger) and small (less than 25 inches) fish except in the 8 vs. 4 f.p.s. test condition. Here a greater proportion of large fish chose the higher velocity channel.

3. The limited number of silver salmon tested during these experiments indicated that this species generally preferred the higher velocity channel.

4. Results of an exploratory test in which 41 steelhead and 57 chinook were presented with a choice between water velocities of approximately 3 and 13 f.p.s. were similar to the preceding test in that 75.6 percent of the steelhead and 89.5 percent of the chinook chose the high-velocity channel.

High-velocity experiments

The performances of steelhead and chinook were measured in water velocities of 13.4 and 15.8 f.p.s. by determining the distance which the fish were able to negotiate through an 85-foot channel. The 13.4 f.p.s. tests were conducted from September 5–7, and the 15.8 f.p.s. tests were conducted on September 9, 10, 14, and 15. A total of 47 steelhead and 91 chinook were tested in the 13.4 f.p.s. flow and 67 steelhead and 130 chinook were tested in the 15.8 f.p.s. flow. The following results were obtained.

1. The performance of steelhead surpassed that of chinook in both 13.4 and 15.8 f.p.s. velocities. At a water velocity of 13.4 f.p.s., 92 percent of the steelhead negotiated the entire length of the channel whereas only 51 percent of the chinook achieved this distance. The performance of both steelhead and chinook declined at 15.8 f.p.s. velocity. Only 51 percent of the steelhead and 5 percent of the chinook negotiated the entire 85-foot channel. A decline in the swimming ability of chinook was noted during the experimental period.

2. Large fish of both species performed better than small fish in both 13.4 and 15.8 f.p.s. velocities.

Rate-of-Movement Experiments

The influence of water velocity upon rate of movement was measured by timing the fish through a 30-foot distance within the channels. Rates were determined at water velocities approximating 2, 4, 6, 8, 13, and 16 f.p.s. These experiments were conducted concurrently with the velocity-preference experiments and high-velocity experiments and utilized the same fish. The following results were obtained:

1. Rates of passage through the channels varied with species and water velocity. Based on median passage times required to negotiate 30 feet, both steelhead trout and silver salmon increased their rate of movement as the water velocity increased from 2 to 8 f.p.s.; steelhead from 4.1 to 5.6 f.p.s. and silver salmon from 3.1 to 5.1 f.p.s. In contrast the rate of movement of chinook salmon decreased from 6.9 f.p.s. in the 2 f.p.s. flow to 5.5 f.p.s. in the 8 f.p.s. flow.

The rates of movement of steelhead and chinook, based on median passage times of the fish which were able to negotiate the 30-foot timing zone, were 4.6 and 3.4 f.p.s., respectively, in the 13.4 f.p.s. velocity and 4.7 and 3.8 f.p.s., respectively in the 15.8 f.p.s. velocity.

3. A standing wave which occurred within the timing zone at a velocity of 6 f.p.s. tended to stop some of the fish for periods ranging from several seconds to several minutes. Steelhead were more affected by this wave than chinook.

4. Large steelhead and chinook were generall faster than small steelhead and chinook at eac velocity tested.

5. Maximum observed swimming speeds (rat of movement in relation to the channel plus th water velocity in which the rate was measured for each species were as follows: steelhead 26. f.p.s., chinook 21.9 f.p.s., and silver salmon 17. f.p.s. These rates are equivalent to 18.3, 14.9 11.9 miles per hour, respectively.

6. There was no evidence that the distance which steelhead and chinook were able to negotiate in flows of 13.4 and 15.8 f.p.s. influence their rates of movement at these velocities Rates of movement of fish which were unable to negotiate the entire channel at these velocities did not differ significantly from those fish which negotiated the entire channel.

7. There was no apparent difference in the rate of movement maintained by steelhead and chinook through the first 30 feet and last 50 feet of th channel in the 13.4 f.p.s. flow. At 15.8 f.p.s velocity the rates of movement of both steelhea and chinook decreased somewhat through the las 50 feet of the channel.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of the following individuals: Gerald B Collins who was responsible for the original planning of the experiments; Carl H. Elling who supervised the experiments; Robert S. Rupp who was in charge of preliminary experiments conducted in 1956 and devised the methods of establishing many of the various flow conditions; and personnel of the Hydraulics Laboratory, U.S. Corps of Engineers, Bonneville Dam for technical assistance with the various hydraulic problems encountered during the experiments. The author is particularly indebted to Robert H. Lander, Biometrics Unit, Bureau of Commercial Fisheries Biological Laboratory, Seattle, for his assistance in designing the experiments and statistical treatment of the data.

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APPENDIX A

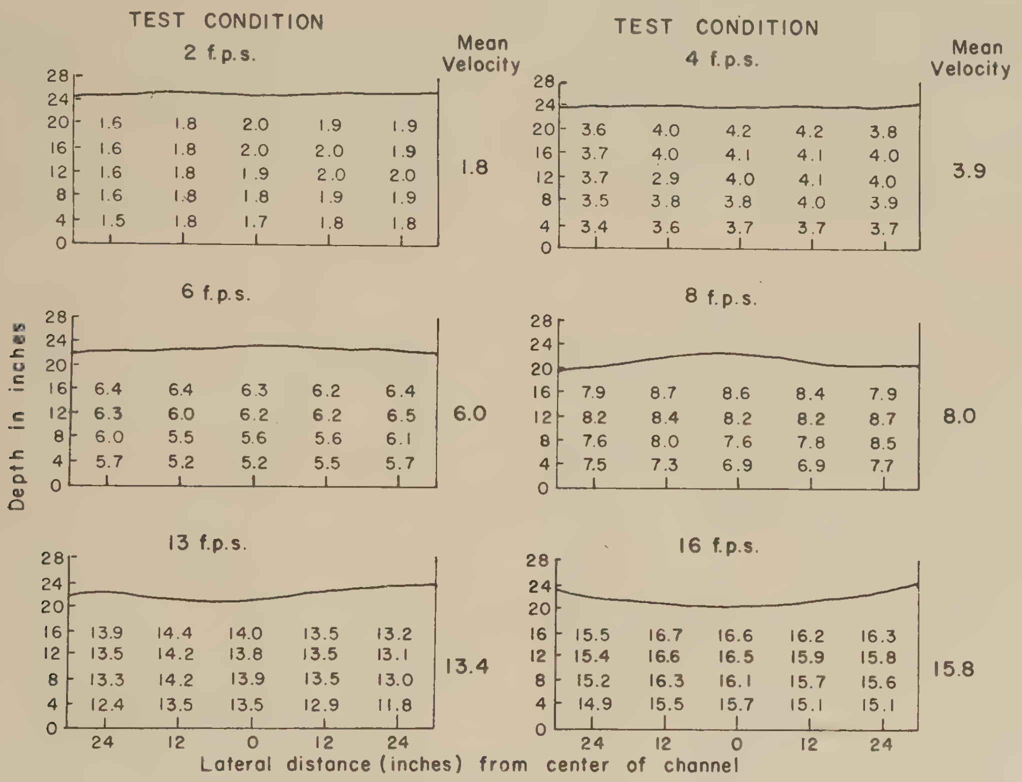

FIGURE A–1.—Examples of the distribution of water velocities in the channel for each of the six test conditions. Entries for each measuring point (depth and distance from the center of the channel) are mean values derived from measurements taken at these points at five different stations between the downstream end of the channel and the upstream limit of the timing zone (point B, figs. 3 and 9). Line at top indicates water surface.

VELOPMENT OF A MATHEMATICAL RELATIONSHIP BETWEEN ELECTRIC-FIELD PARAMETERS AND THE ELECTRICAL CHARACTERISTICS OF FISH

By Gerald E. Monan, *Fishery Biologist,* and Derek E. Engstrom, *Physicist*

ABSTRACT

few of the electrical characteristics of fish were de- l and studied as the criteria for producing a speci- bbserved reaction. Voltages and currents applied small test cell containing a live fish were measured. n the use of an electrical analogue of the cell con- s, these data were reduced to the equivalent param- applied to a mathematical model representing the The resulting values of resistivity and power density computed for this model were then used to describe the corresponding fish characteristics. Application of pulsed voltages to the cell demonstrated a minimum power density below which no reaction was observed. Equations were then derived to relate this value to corresponding electrical conditions that would exist at an electrical guiding installation.

he use of electric fields is presently being stigated as a possible method of diverting for safe passage around hydroelectric dams, aiding in the perservation of the salmon ries.[1]

major problem of this investigation is the uation of an electric field as a motivating ulus. Prior to the research reported upon few, if any, methods have been developed bserve or determine accurately those portions field pattern which motivate the behavior a fish. Therefore, the optimum electrical meters of a particular, effective guiding llation may not apply at some other site. ther words, so little is known about how an rical field stimulates a fish that it is difficult lesign a successful electrical-guiding device. nsive and costly experimentation has been ssary at each new installation to obtain necessary parameters for an effective rical-guiding device.

An investigation of this problem indicates that an adequate solution would include a mathematical method of relating electric-field parameters to the electrical characteristics of the fish. These characteristics control the response of the fish to electricity and thus define for the fish specific regions in an electrical field. However, because of the complexity of the biological structure involved, a precise description of these characteristics is impossible. The mathematical process therefore, must utilize an electrical analogue to facilitate such a description.

The research presented here has three objectives: (1) To develop a mathematical model to serve as the electrical analogue of a fish, (2) to find an evaluation procedure which will determine the electrical properties and processes within the model, and (3) to develop a method to relate these model characteristics to the parameters of the electric fields to be used in proposed fish-guiding devices.

MATERIALS AND METHODS

The experiments were conducted at the Bureau of Commercial Fisheries Biological Laboratory,

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E.--Approved for publication April 17, 1962.

son, James E., and Rea Duncan. Manuscript in preparation. The ment and appraisal of methods of diverting fingerling salmon with ity at Lake Tapps. Bureau of Commercial Fisheries Biological tory, Seattle, Wash.

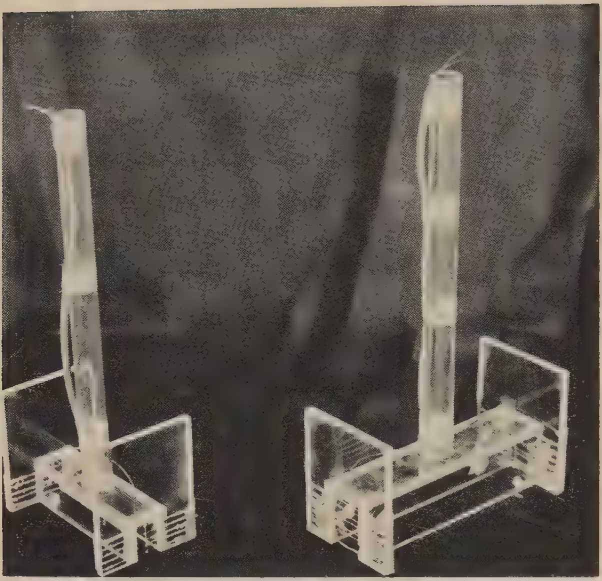


FIGURE 1.—Plastic cells used to contain fish while testing.

Seattle, Wash., from November 27, 1958, to January 9, 1959. The fish used were 0 age-group sockeye salmon (*Oncorhynchus nerka*). These fish were obtained from the Winthrop National Fish Hatchery in September, 1958, and were kept in the laboratory holding facilities until their transfer to the experimental area.

The general method of laboratory investigation involved measuring voltages and currents applied to a small, plastic test cell (fig. 1) containing a live fish. Measurements were carried out with the fish facing either the positive or the negative electrode. These parameters were measured coincident with a specific observable reaction of the fish. Measurements of applied voltage were made from electrodes positioned within, and at opposite ends of, the cell. These electrodes were designed so the electrical resistance between them would be completely controlled by the contents of the cell. It was also necessary to reduce the volume of the surrounding body of water to a minimum in order to obtain measurements which were analogous to functions of the electrical characteristics of a fish. Reactions produced in the fish were created by applying the necessary voltage across the cell.

The cell voltages used in the calculations were the lowest applied values to which the fish appeared to respond. This response was selected because it could be easily observed and because the stimulus threshold was well defined. When the applied voltage reached the threshold value, a viole swimming motion was observed. This reacti could be considered equivalent to the musc response caused by the rheobase potential (Mitc ell, 1948), and would correspond to the thresho reaction reported in later publications (Fishe 1950; Cattley, 1955). Since this observed thres old phenomenon is a property of the biologic structure of the fish, any corresponding electri field gradient should produce the same effec Therefore, this response defined a characterist of the fish that could be related to field-patte parameters.

HOLDING FACILITIES

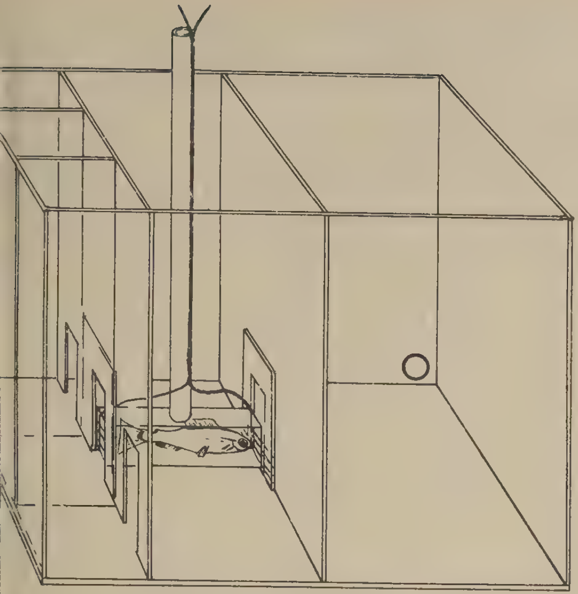
Holding facilities were set up adjacent to th experimental area in order to provide ease operation and to minimize any change in wate conditions between the holding troughs and th cell. Fish were held here at least 4 hours pri to testing.

Equipment for this installation included thre wooden troughs, 22 cm. wide by 24 cm. deep b 196 cm. long, and a 1042-liter wooden tank Dechlorinated city water was supplied to the tan through a float valve. From the tank, water wa pumped to a head trough which in turn supplie the three holding troughs. Approximately 7 percent of the flow from the holding troughs wa diverted back into the main tank, and 30 percent was drawn off as waste. A thermostatically controlled refrigeration unit kept the water temperature at approximately 50° F.

APPARATUS

The major portion of the experimental apparatus was made up of the plastic tank and test cells and the electronic measuring and testing equipment. The plexiglass tank had inside dimensions of 25 cm. by 25 cm. by 38 cm. and had one fixed partition and one adjustable partition. A test cell (fig. 2) was placed between these partitions, and the adjustable partition was positioned and clamped in such a manner as to hold the cell tightly between the two partitions. Electrodes made of duralumin were placed at both ends of the tank to permit the application of the test currents.

Two cells of different size were used in order to accommodate the range of fish sizes tested. Cell number one had inside dimensions of 2.54 cm. wide, 3.81 cm. deep, and 15.88 cm. long; whereas



URE 2.—A test cell in position within the experimental tank.

number two was 1.59 cm. wide, 2.54 cm. deep, 11.43 cm. long. Each cell was equipped h nylon restraining threads stretched horizon-y across both ends. The quanity of restraining terial was kept at a minimum by using only threads per end for cell number one and three eads per end for cell number two. Monotoring ctrodes were placed in each cell opening to asure the voltage drop across the cell. The ds for these electrodes were routed through cell wall and up the handle to the external cuit.

Three types of monitoring electrodes were used. e first arrangement consisted of a ¼-inch wide, inless steel strip, cemented to the top wall, t inside each cell opening. The second type s a ¼-inch mesh screen which covered the two s of the cell, and the third type consisted of a gle wire stretched horizontally across the cell enings. Experimentation with all three types ealed that the fish were not sensitive to the ximity of a conducting plane. This informa-n was important for consideration in the design uture cells.

Vater was obtained from the holding facilities was gravity fed to the tank from a 14-gallon ervoir. The rate of flow through the test cell kept at approximately 2 gallons per hour. ter resistivity was controlled by the introduc-n of NaCl.

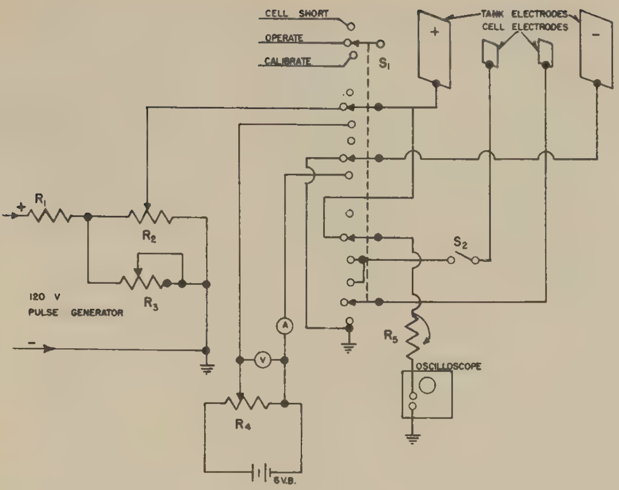


Figure 3.—Circuit diagram of the complete testing unit.

The electronic circuitry enabled a square wave pulse of the desired amplitude and duration to be applied to the cell (fig. 3). Electronic switching equipment, controlled by the investigator (described in detail by Volz (1962)) connected the output of a d.c. (direct current) generator to the test circuit at preset intervals and for preset durations. The voltage applied to the circuit was essentially a square wave pulse with an amplitude of 120 volts and a duration of 50 milliseconds.

The circuit functions as follows: When switch S_1 is in the operate position, the functioning circuit is the operate circuit (fig. 4a). In this case, resistors R_1, R_2, and R_3 combine to form an adjust-

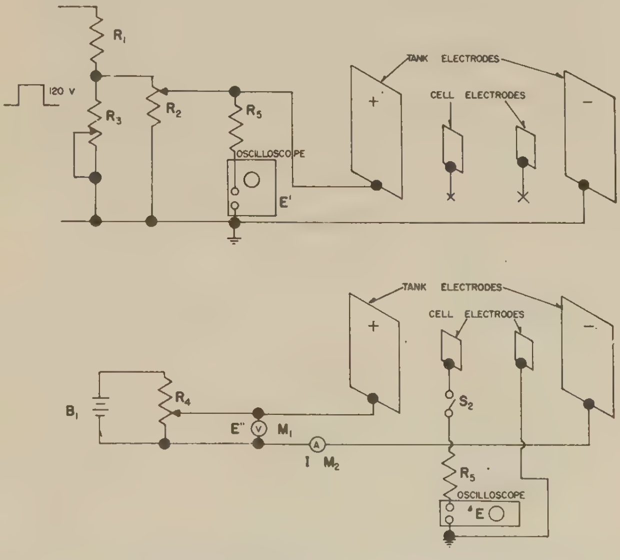


Figure 4.—Circuit diagram of the testing unit: (above) operate configuration; (below) calibrate configuration.

able voltage divider that reduces the 120-volt input pulse to the required voltage applied to the tank. This voltage is applied to the tank electrodes and is monitored on the oscilloscope by means of the monitoring electrodes. Resistor R_5 is used to change scale readings on the oscilloscope by one-half, when necessary, in order to achieve the maximum possible accuracy.

When switch S_1 is placed in the calibrate position, the functioning circuit is the calibrate circuit (fig. 4b). In this case battery B and resistor R_4 supply an adjustable d.c. voltage to the tank electrodes. The voltage drop across the cell is now measured on the oscilloscope. Switch S_2 prevents current from flowing in the monitoring circuit until the operator is ready to record the reading. This operation is necessary in order to prevent the electrodes from becoming polarized and giving erroneous readings. After the readings have been taken, depolarization is accomplished by closing switch S_2 and placing switch S_1 in the "cell short" position. With the switch in this position, the cell electrodes are shorted, thus returning the circuit to equilibrium.

MEASUREMENT PROCEDURE

After preliminary experimentation, a specific measurement procedure was adopted. The fish to be tested was taken from the holding trough and was placed in the plexiglass tank. The test cell was then lowered over the fish and positioned so that the openings at the ends of the cell coincided with the openings in the partitions. The resistivity of the water entering the test cell was then measured with a standard resistivity bridge.

After the fish was allowed a two-minute rest, switch S_1 was placed in the operate position, and the electronic pulsing device was triggered. Pulses with a duration of 50 milliseconds were then automatically applied at intervals of 20 seconds. Between each pulse application, the potentiometer (R_2) was manually rotated to increase the pulse amplitude. When the reaction level was reached, the fish jumped violently, and the operator, observing this reaction, recorded the pulse voltage from the oscilloscope.

The battery voltage (B_1) was used to establish the relationship between the pulse voltage across the tank and the actual voltage across the cell. The desired level of current was set, and the voltage was recorded from the voltmeter (M_1). With switch S_2 closed, switch S_1 was moved to th cell short position and the cell electrodes wer shorted for 30 seconds. With switch S_2 open switch S_1 was turned to the calibrate position Switch S_2 was then closed, and the voltage wa immediately recorded from the oscilloscope Three levels of current were used for each fis tested, and measurements were repeated at leas twice at each level to insure accuracy.

After being tested, each fish was lifted from th cell in a net, and after the excess water, clingin to the fish, was eliminated, the fish was placed i a graduated cylinder partially filled with water The volume of the displaced water was the recorded as the volume of the fish.

The complete testing procedure took approximately 15 minutes per fish. After the volum measurement was completed, each fish was returned to the appropriate trough, where it was held for several days. No mortalities occurred among the fish tested.

ANALYSIS PROCEDURE

The symbols listed below are used in the discussions that follow:

ρ_f=fish resistivity.
ρ_w=water resistivity.
V_f=fish volume.
V_c=cell volume.
L=fish length.
D=distance between cell electrodes.
R=resistance of the cell containing the fish.
R_a=resistance of the cell without the fish.
E=d.c. voltage drop across the cell.
E''=d.c. voltage applied to the tank.
E'=reaction voltage applied to the tank.
V=guiding-field gradient.
P_{fv}=power density in the fish.
P_{wv}=power density in the water.
I=d.c. current through the cell.
m=empirical function of ρ_w and ρ_f.

Appendix A contains a glossary which may be useful to readers who are not familiar with electrical laws and terms. The following discussion is purposely brief; however, the subject is covered in more detail in appendix B. The mathematical model of the fish was developed by constructing an electrical analogue of the contents of the test cell. The analogue was developed by dividing the cell into a number of rectangular parallelepipeds, one of which represented the fish and the remaining ones represented the water within the cell. The size of the parallelepiped representing fish was dependent upon the size of the fish, reas the dimensions of the remaining paral- ipeds were functions of both cell and fish netry.

he correct partitioning of the cell's contents parallelepipeds was governed by the following irements: (1) the calculated fish resistivity t remain constant as the water resistivity is ed over a specified range, (2) there must be a tical limitation on the complexity of the lting equations, and (3) the accuracy require- ts of the resulting equations must not exceed capabilities of existing measuring techniques. se are the restrictions which were used in sing the mathematical model of the fish.

the partitioning scheme, each parallelepiped he cell model was treated as a resistive-circuit ponent. The end or cross sectional bound- s served as connecting terminals, whereas the aining surfaces were considered nonconducting. resistance of each of the parallelepipeds was ted to the resistivity of its enclosed medium by g Ohm's Law. The result was a set of equa- s called component equations which related dimensions, fish dimensions, water resistivity, fish resistivity to the resistance of a corre- ding circuit component. Thus, an analogue uit of the cell's contents was devised by re- ing each parallelepiped of the cell model with quivalent two-terminal resistive component. total resistance of this analogue circuit was gnated to be the cell's resistance. An equa- was obtained by using the known properties of tors to relate this resistance to the resistance ch component. This equation was called the uit equation. By substitution of the compo- equations for the resistance values in the uit equation, a relationship was obtained be- n the cell resistance and the resistivity of the model. Thus, the resulting equation provided ethod of evaluating a specific property of the

he transformation from the actual cell to that he model of the cell's contents can be more ly visualized by mentally subdividing the al cell volume into infinitesimal volume ele- ts. These elements would be of equal volume can be called differential volume elements ilar to the units used in the differential theory lculus).

he transformation consists of transferring each element of the cell volume into a parallelepiped in the model of the cell's contents. The correct distribution of volume elements should be carried out in such a way that the total power in each parallelepiped will be equal to the power dissipated in a corresponding circuit component for all values of water resistivity. In order to complete the transformation, the lines of current flow can be rotated in each differential element without changing the power dissipated by the element. This allows these current lines to be arranged to correspond with those current lines which would be expected to exist in each parallelepiped. After considerable preliminary experimentation, two configurations were chosen which best fulfilled the previously established criteria.

The first partitioning plan divided the cell's contents into four parallelepipeds; three represented the total water in the cell. The fourth parallelepiped, which represented the fish, was designated as the fish model. The corresponding analogue circuit was composed of four resistors (R_1, the fish; and R_2, R_3, and R_4, the water) connected in a series-parallel network. This arrangement was satisfactory in all ranges of water resistivities tested except when the resistivity of the fish was greater than the resistivity of the surrounding water. It was in this region that this arrangement had a point of discontinuity.

In order that this difficulty might be avoided, the volume elements were resolved in a different manner for this area of operation. In this partitioning system, the cell's contents were divided laterally into two rectangular parallelepipeds, one representing the fish and the other representing the total water in the cell. The corresponding analogue circuit was composed of two resistors (R_1, the fish; and R_2, the water) connected in series.

EVALUATION PROCEDURE

The resistivity of the fish model was found by using the measured resistivity of the water in the cell and the resistance of the cell. The values of R were found from the slope of a plot of cell voltage (E) vs. cell current (I) for each fish tested. Figure 5 shows an example of one of these graphs. A similar graph (fig. 5) was made from data taken with the cell empty in order to find the value of R_a. One of these graphs was made for each series of fish tested. Because the value of R_a is directly proportional to the resistivity of the

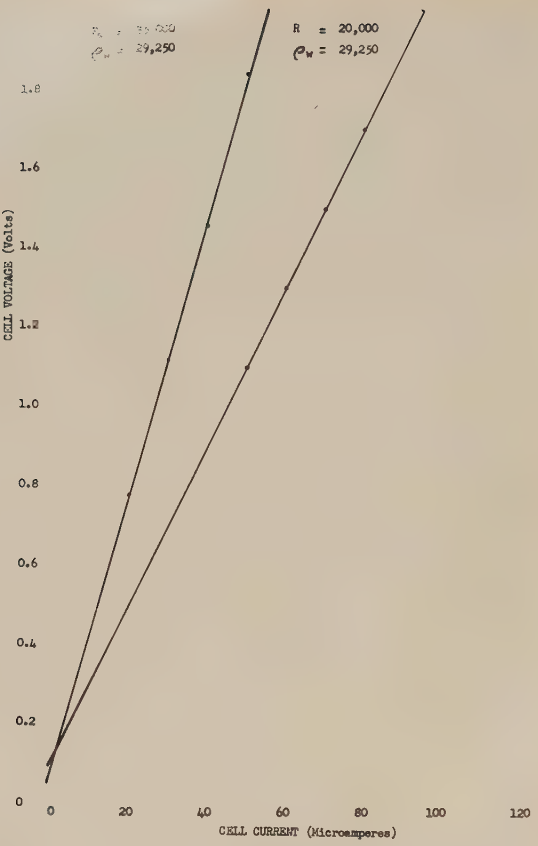


Figure 5.—A plot of cell voltage (E) vs. cell current (I); first for an empty cell and then for the cell with the test fish enclosed. The resistance of the empty cell (R_a) and the resistance of the cell with the fish enclosed (R) were found from the slope of their respective graphs.

water in the cell, it was easy to calculate from this single value of R_a the R_a's for the rest of the series. With the use of these values and other measured parameters, such as fish volume, fish length, and distance between electrodes, the values of fish resistivity (ρ_f) were found. The figures for fish length were obtained from the graph illustrated in figure 6.[2]

The power density in the fish model was determined by applying Kirchhoff's Voltage Law to the analogue circuit of the cell's contents. With this approach, the total power in the fish model was related to a voltage applied across the cell's contents. The voltage that was applied to the cell was considered as being applied to the analogue circuit terminals, as represented by the ends (the cell. The voltage value used in the compu tation was the applied cell voltage which produce the specific swimming like motion chosen as o desired reaction. By application of Kirchhoff Voltage Law and our component equations, th actual voltage applied across the fish model wa determined. The power density in the fish mod was determined by using Joule's Law, the fis model's dimensions, the voltage applied to th model, and the component resistance of the mode The equation describing this relationship provide a method of evaluating the rate at which an elec trical process takes place within a fish.

The range of water resistivities, over whic the configurations and their corresponding equa tions were useful, was established by varying th water resistivity (ρ_w), calculating the resistivit of the fish (ρ_f), and observing within what rang of water resistivities the resistivity of the fis remained relatively constant.

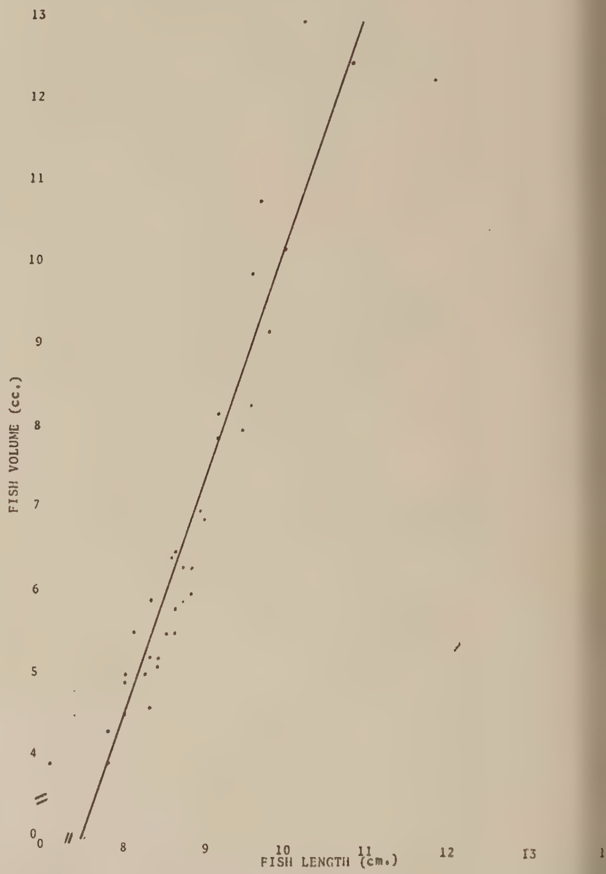


Figure 6.—Length-volume relationship used to provid the additional parameter fish length (L) in the four-bod equation.

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[2] When the four-body equation was derived, it became necessary to add a previously unneeded parameter, fish length (L). The lengths and volumes of a random sample of experimental fish were measured and a plot of fish length (L) vs. fish volume (V_f) was made to obtain this measurement. From this graph, approximate values of fish length were obtained by using the recorded values of fish volume (V_f) from the previous experiments.

he theory and complete mathematical deriva- of the formulas used in computing fish tivity and power density are found in ndix B.

order that the third objective of our research t be fulfilled, the power density in the fish was related to the corresponding power ity (P_{wv}) and voltage gradient (V) in an open of water. The complete derivation and nation of the relationship between P_{fv} and an be found in appendix C.

RESULTS AND DISCUSSION

ble 1 shows the models of the test cell that derived, the corresponding analogue circuits, ange of water resistivities for each and the tions used, to solve for ρ_f and P_{fv}.

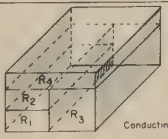
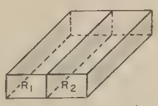
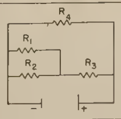
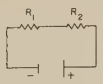
e formula derived for relating cell voltage ents and power densities to open water ents and power is as follows:

$$_wPwv = (m^2 \rho_f P_{fv}) = V^2 \text{ where } m=f(\rho_w \rho_f)$$

complete derivation and explanation of this ula can be found in appendix C.

e symmetry of the equations and configura- is similar to those experienced with standard and parallel electrical circuits. Basic laws ectricity can be applied to these configura- just as if they were composed of common mercial resistors. For example, in a resistance ork with two resistors in parallel, if one ance approaches zero and the other remains ant, the total resistance approaches zero.

E 1.—*Formulas derived for computing fish resistivity power density; shown with the corresponding test-cell dels and analogue circuits. The limits of usefulness,* ***ed on*** *water resistivity, are also shown.*

RIVED TEST	Four body —series— parallel	Two body —series
CELL MODELS		 Conducting planes are illustrated as shaded surfaces
LOGUE CIRCUIT		
TIO FOR ρ_f	$\rho_f = \frac{\rho_w[RR_aV_fL-2V_fR_a(R_a-R)(D-L)]}{RR_aV_fL-V_fR_a(R_a-R)(D-L)+\rho_wD^2L(R_a-R)}$	$\rho_f = \rho_w + \frac{\rho_w^2D^2}{R_a^2V_f}(R-R_a)$
TION FOR P_{fv}	$P_{fv} = \left(\frac{EE'}{E''}\right)\left(\frac{\rho_wD}{\rho_f\rho_wD^2L+2R_aV_f(D-L)(\rho_w-\rho_f)}\right)^2L^2\rho$	$P_{fv} = \left(\frac{E'E}{E''}\right)^2\left(\frac{R_a}{R}\right)^2\left(\frac{\rho f}{\rho^2D^2}\right)$
OF USEFULNESS	$1 \leq \frac{\rho_w}{\rho_f} \leq 20$	$1 \geq \frac{\rho_w}{\rho_f} \geq 0,75$

If, on the other hand, two resistors are connected in series and the value of the first resistor approaches zero and that of the second resistor remains constant, the total resistance of the circuit approaches the value of the second resistor. These same principles are applied to the resistance elements of the model of the cell's contents.

In order that the situation in which the resistivity of the water (ρ_w) is greater than the resistivity of the fish (ρ_f) might be accurately represented, the configuration and corresponding equation starting with two resistors in parallel are used. This equation reaches an extreme limit when the resistivity of the water (ρ_w) is infinite. When the resistivity of the water (ρ_w) is infinite, the resistance of the cell is equal to the resistance of the fish. By expanding this two-body, parallel configuration into a four-body, series-parallel network, this limit disappears. In the four-body, series-parallel network, when the resistivity of the water (ρ_w) is infinite, the resistance of the cell (R) is infinite; and when the resistivity of the water (ρ_w) is zero the resistance of the cell (R) also is zero.

In order that an accurate reflection of the situation in which the resistivity of the water (ρ_w) is less than the resistivity of the fish (ρ_f) may be achieved, the configuration and corresponding equation with two resistors in series are used. This equation reaches an extreme limit where the resistivity of the water (ρ_w) is zero. In this case, the resistance of the cell (R) is equal to the resistance of the fish.

The equation developed to relate power density in the cell to power density in an open body of water is not completely satisfactory. When the volume of the cell is expanded to infinity in our configuration, the boundaries no longer enclose finite regions and therefore exhibit an impossible field condition. For elimination of the effects of this property it was necessary to put an empirical function (m) of ρ_w and ρ_f into the equation. This empirical function will have to be determined by further experimentation.

Appendix D illustrates some qualitative values of fish resistivity and power density that were calculated to observe the practicability and validity of the derived analytical processes. With the use of the formulas that were derived, according to their restrictions, the average value of fish resistivity was calculated for the fish tested. When measured from end to end, with the fish acclimated at 49° F., this resistivity was 1,380 ohm centimeters. The large deviations in the values for the fish tested are primarily due to two causes: (1) a lack of accurate data on fish length and, (2) leakage current between the cell flange and the tank partitions. If the cell was not placed exactly in the same position each time, the dimension changes of the minute spaces between the cell flange and the tank partitions caused an error between the resistance of the cell with the fish in (R) and the resistance of the cell empty (R_a). Because of these errors, further work should be done before the absolute numerical values can be considered correct.

During the experiment, several interesting phenomena were observed. One of these was the apparent dependence of the reaction threshold upon pulse-rise time. Although the available equipment prohibited the variation of pulse-rise time, the fish was observed to withstand, without irritation, a much greater level of voltage when it was applied as a continuous voltage gradient. Mitchell (1948) found this to be true also in work with individual nerves.

It was also noticed that the reaction level appears to be a funtion of fish size when the fish is facing the positive pole; yet, when the fish faces the negative pole, this level is constant. When the fish was facing the negative pole, the reaction level was generally lower than it was when the fish was facing the positive pole (table 2). This has also been observed by other investigators (Eggen and Sheckels, 1954; McMillan, Holmes, and Everest, 1937[3]).

CONCLUSIONS

1. A mathematical model can be devised to serve as the electrical analogue of a fish.

2. The techniques developed in this work can provide a means of evaluating the electrical properties and processes within the model and thus provide a practical method of evaluating some electrical characteristics of a fish.

3. Power density can be used to describe an electrical criterion required to produce a specific reaction in a fish.

4. The mathematical techniques developed her indicate that power density, as a reaction criterio can be related to electric field parameters.

5. Additional experimentation will be require to develop the relationship between power densit and the corresponding voltage gradient in a unbounded body of water.

TABLE 2.—*The relationship of the average reaction pow density to fish volume and polarity orientation*

Pole fish is facing		Fish volume (cc.)		P_{f},[1] (microwatt per c	
Positive	Negative	Range	Average	Range	Av ag
	x	3.9 to 9.0	6	0.51 to 2.51	
	x	11.0 to 22.0	15	0.32 to 1.64	
x		3.9 to 9.0	6	0.61 to 3.31	
x		11.0 to 22.0	15	0.84 to 8.44	

[1] P_{f}, must be applied within 2 milliseconds, since a pulse with a rise ti of not greater than 2 milliseconds was used.

RECOMMENDATIONS

The experimentation reported here should b furthered, and the following improvements shoul be employed:

(a) The test cell used in future experiment should resemble, in principle at least, the cell in figure 7. This design reduces the possibility o leakage currents, provides easier access to the cell and enables closer observations of the fish.

(b) The electronic equipment should be well shielded and grounded.

(c) Alternating current should be used wherever possible to avoid polarization effects.

(d) The ends of the cell should be perforate conducting planes, erected perpendicular to the major cell axis.

(e) The incremental increase in pulse amplitud should be small in magnitude and constant in rate

(f) A consistent handling procedure should b used for each fish.

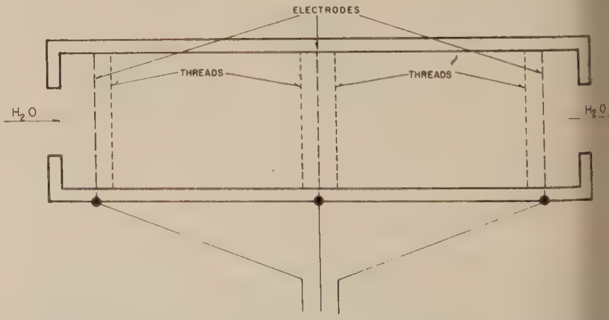


FIGURE 7.—Proposed test cell, incorporating the recom mended improvements to eliminate leakage currents.

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[3] McMillan, F. O., H. B. Holmes, and F. Alton Everest. 1937. The response of fish to impulse voltages. A report on investigations conducted at the Tablerock site near Medford, Oreg., between August 25, 1937 and September 18, 1937. 15 p. Typewritten. A copy of this report is available at the Bureau of Commercial Fisheries Biological Laboratory, Seattle, Wash.

) The length of each fish tested should be rately measured and recorded.

SUMMARY

ectrical fish guiding is being developed for use otecting natural fish runs where their migra- is threatened by manmade obstacles. A r problem in this development is the evalua- of an electric field as a motivating stimulus. der that a precise method of evaluation might tablished, a method of analysis was developed h employed a mathematical model of a fish.

e fish was confined in a small plastic test through which water was circulated. The rical characteristics of the cell's contents er and fish) were determined by measuring ges and currents applied to the cell. A math- ical model of the cell's contents was then ed by mentally dividing the test-cell volume several parallelepipeds. One of the parallel- ds was designated to represent the fish, eas the others represented the water within ell. The characteristics of this model were ed as those properties necessary to produce ectrical analogue of the cell's contents. Since roperties of the water portion of the analogue known, the characteristics of the fish portion determined by measuring the electrical pa- ters applied to the cell. The entire process ed: (1) the voltage applied between the cell odes; (2) the electrical resistance of the cell, the fish and without the fish; (3) the water ivity; (4) the length of the fish; (5) the ne of the fish; (6) the cell length or separation cell electrodes; and (7) the formulas derived ate the resistivity and power density of the l to the measured parameters.

e model characteristic, power density, was mined to be a criterion for producing an ved reaction. The applied voltages used ese power calculations were the minimum s to which the fish appeared to react. There- the resulting power density value was a pro- controlled by the fish.

dy of the variations in the threshold of on revealed that the power density neces- or this reaction increased as the size of the ncreased, provided the fish was facing the ve pole. If the polarity was reversed, the hold remained constant over the range of fish sizes tested. The two levels of power density converged as the fish size decreased. With the fish facing the positive pole, the average value of power density ranged from 1.4 to 3.8 μw/cc. over a corresponding fish-volume variation of 6 to 15 cc. When the fish faced the negative pole, values of 0.8 to 0.9 μw/cc. were obtained over the same volume range.

By expanding the cell dimensions, in our calculations, we found it possible to obtain a simple relationship between power density and the equivalent voltage gradient in an unbounded body of water. This gradient is the variable that would be applied in an electrical fish-guiding field pattern. The calculated gradient would permit the identification of portions of any field pattern as being capable or incapable of producing the reaction observed in the laboratory. Because of the manner in which the test cell's contents were subdivided, the equations derived for the open-water gradient contain a proportionality function, with constants that must be evaluated empirically. Therefore, this particular phase of the work is incomplete. Examination of the results of this work, however, indicates that a mathematical model can be devised to serve as the electrical analogue of a fish, and the techniques that were developed can provide a practical method of evaluating some electrical characteristics of fish. Additional experimentations, incorporating the techniques developed herein and incorporating the recommended improvements, will certainly be of value to the electrical-guiding program.

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APPENDIX A

GLOSSARY

1. Joule's Law: That portion of the power input to any device which is equal to the product of the resistance of the conductors forming the winding of the device and the square of the current through this winding is always converted into heat. That is, when a current I flows through a resistance r, heat is always "dissipated" in this resistance, and the rate of dissipation is $P_h=rI^2$ [1]

2. Kirchhoff's Network Laws: (a) The algebraic sum of the currents coming to any junction in a network of conductors is always zero. (b) The algebraic sum of the potential drops around any closed loop in a network of conductors is always zero.[1]

3. Ohm's Law: If a steady difference of potential V (in volts) is impressed across a conductor which (a) is held at constant temperatur and in which (b) there is no internal emf, $V=r$ where I is the steady current in amperes whic will flow through the conductor and r is the facto of proportionality called the resistance of th conductor. The drop in potential V is therefor equivalent to the drop in potential rI, this latte being called the resistance drop.[1]

4. Resistance: The opposition offered by substance or body to the passage through it of a electric current.[2]

5. Resistivity: The proportionality facto between current density and electric intensity A property of a medium having the same valu as the resistance measured between opposit faces of a unit cube of the medium, expressec in ohm-units.[3]

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[1] This definition is taken from the following source: Eshbach, Ovid W. 1955. Handbook of Engineering Fundamentals. 2d ed., John Wiley and Sons, Inc., New York. 1262 pp.

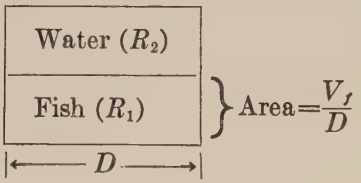
[2] This definition is taken from the following source: 1946. Webster's Collegiate Dictionary. 2d ed. G. C. Merriam Co., Springfield, Mass. 1,174 pp.

[3] Author's definition.

APPENDIX B

Theory and mathematical derivation of the formulas used in computing ρ_f and P_{fv}.

The two-body equations for (ρ_f) and (P_{fv}) were developed in the following manner:



Then, for the total cell resistance R:

$$R=\frac{R_1R_2}{R_1+R_2} \qquad (1)$$

Where:

$$R_1=\frac{\rho_fD^2}{V_f}\quad R_2=\frac{\rho_wD^2}{V_c-V_f}$$

$$V_c=\frac{\rho_wD^2}{R_a}\quad R_2=\frac{\rho_wD^2R_a}{\rho_wD^2-R_aV_f}$$

Substituting for R_1 and R_2 in (1) and solving for ρ_f we get:

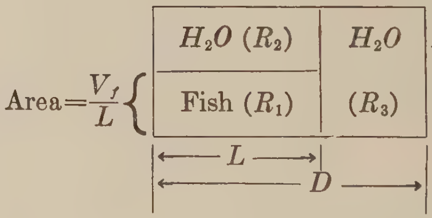
$$\rho_f=\frac{\rho_wRR_aV_f}{RR_aV_f+\rho_wD^2(R_a-R)} \qquad (2)$$

and for power density:

$$P_{fv}=\left(\frac{E'E}{E''}\right)^2\frac{1}{R_1V_f}=\left(\frac{E'E}{E''}\right)^2\frac{1}{\rho_fD^2} \qquad (3)$$

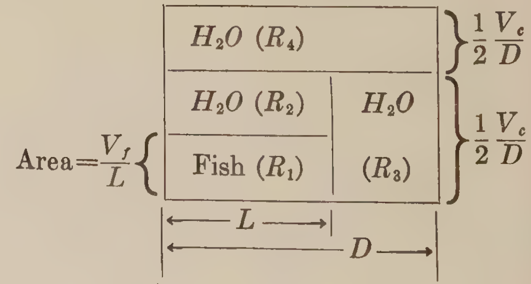
The expansion to a three-body and a four-body arrangement was done in the following manner:

Three-Body



$$R=R_3+\frac{R_2R_1}{R_1+R_2} \qquad (4)$$

Four-body



$$=\frac{(R_4)\left(R_3+\frac{R_1R_2}{R_1+R_2}\right)}{R+\left(R_3+\frac{R_1R_2}{R_1+R_2}\right)} \qquad (5)$$

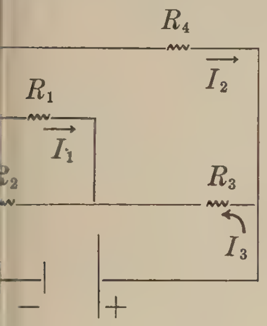
$${}_4=\frac{\rho_f L^2}{V_f},\ R_2=\frac{\rho_w L}{\frac{V_c}{2D}-\frac{V_f}{L}}=\frac{2\rho_w L^2 R_a}{(\rho_w LD-2V_fR_a)}$$

$$=\frac{\rho_w(D-L)}{\frac{V_c}{2D}}=\frac{2R_a(D-L)}{D},\ R_4=\frac{\rho_w D}{\frac{V_c}{2D}}=2R_a$$

stituting into (5) and solving for ρ_f gives:

$$\frac{\rho_w[RR_aV_fL-2V_fR_a(R_a-R)(D-L)]}{R_aV_fL-2V_fR_a(R_a-R)(D-L)+\rho_wD^2L(Ra-R)} \qquad (6)$$

n, for power density we solve for the current in the following network.



I_1, I_2, I_3=loop currents

$$E_c=\frac{E'E}{E''}$$

$$\begin{array}{ccc|l} I_1 & I_2 & I_3 & \\ +R_2) & R_2 & R_2 & =0 \\ R_2 & (R_4+R_3+R_2) & (R_2+R_3) & =0 \\ R_2 & (R_2+R_3) & (R_2+R_3) & =E_c \end{array}$$

power density in the fish is:

$$P_{fv}=I_1^2R_1\frac{1}{V_f} \qquad (7)$$

ng for the current I_1:

$$=\frac{E_c\begin{vmatrix} R_2 & R_2 \\ (R_4+R_3+R_2) & (R_2+R_3) \end{vmatrix}}{\begin{vmatrix} (R_1+R_2) & R_2 & R_2 \\ R_2 & (R_4+R_3+R_2) & (R_2+R_3) \\ R_2 & (R_2+R_3) & (R_2+R_3) \end{vmatrix}}=E_c\frac{R_{31}}{\Delta R}$$

Then:

$$P_{fv}=E_c^2\left(\frac{R_{31}}{\Delta R}\right)^2\frac{R_1}{V_f} \qquad (8)$$

Expanding the determinant factors and substituting for the resistance values in the resulting equation we obtain the following:

$$P_{fv}=\left(\frac{EE'}{E''}\right)^2\left(\frac{\rho_wD}{\rho_w\rho_fD^2L+2R_aV_f(D-L)(\rho_w-\rho_f)}\right)^2L^2\rho_f \qquad (9)$$

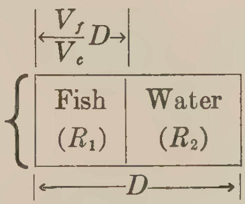
The simplicity of the resulting power density equation was achieved by the manner in which the dimensions of the individual volume elements were chosen. The geometric similarity between these elements reduced the complexity, indicated by the expansion of (8), to the simplicity of equation (9). Such a simplification is desirable for the practicability of processing data. However, it can be expected to limit the range of usefullness of the equation.

In the course of our studies, there was reason to reduce the water resistivity to a value below that obtained for the fish. We did this to check the results of previous measurements. When we attempted to evaluate our data, we found that the measured parameters forced us to work in and near a region of discontinuity that was a characteristic of our equation for (ρ_f). This condition occurred when, for (6):

$$RR_aV_fL-2V_fR_a(R_a-R)(D-L)+\rho_wD^2L(R_a-R)=0$$

To avoid this difficulty, we resolved our volume elements in a different manner for this region of operation. Hence, for the two-body case:

Area$=\frac{V_c}{D}$



$$R=R_1+R_2$$

$$R_1=\frac{\rho_f\frac{V_f}{V_c}D}{\frac{V_c}{D}}=\frac{\rho_fV_fR_a^2}{\rho_w^2D^2}$$

$$R_2=\frac{\rho_w\left(D-\frac{V_f}{V_c}D\right)}{\frac{V_c}{D}}=R\left(1-\frac{V_fR_a}{\rho_wD^2}\right)$$

Substituting and solving for ρ_f we get:

$$\rho_f=(\rho_w{}^2)\left(\frac{D^2}{R_a{}^2V_f}\right)(R-R_a)+\rho_w \tag{10}$$

And:

$$P_{fv}-\left(\frac{E'E}{E''}\right)^2\left(\frac{R_a}{R}\right)^2\frac{\rho_f}{\rho_w{}^2D^2} \tag{11}$$

Notice that for equation (10), there exists no point of discontinuity, as was present in equation (6).

Having derived these equations, we determined that they satisfied our requirements by using the following methods:

1. If the fish model is electrically homogeneous and has a characteristic resistivity ρ_f, then when $\rho_w=\rho_f$, $R_a=R$. Observing equations (2), (6), and (10), we see that in each case, where $R_a=R$, this condition is satisfied.

2. If the resistance R were measured continuously as ρ_w was varied from $\rho_w=0$ to $\rho_w=\infty$, we would expect the functions R and $\frac{\delta R}{\delta\rho_w}$ to be continuous over the range of variation. This is because we consider our cell to contain linear, bilateral resistive elements. To check the fulfillment of this condition, we examined the ratio $\frac{1}{R}\frac{\delta R}{\delta\rho_w}$ at the point where $\rho_w=\rho_f$. If the condition is satisfied, then:

$$\left[\frac{1}{R_{2s}}\frac{\delta R_{2s}}{\delta\rho_w}=\frac{1}{R_{4P}}\frac{\delta R_{4P}}{\delta\rho_w}\right]@\rho_w=\rho_f$$

Where:

R_{2s}=the two-body series function

R_{4P}=the four-body parallel function

Using equation (6) and solving for R as a function of ρ_w, we get:

$$R=\frac{A\rho_wB\rho_f+C(\rho_w-\rho_f)}{B\rho_f+(C+F)(\rho_w-\rho_f)} \tag{12}$$

Where:

$$A=\frac{D^2}{V_c},\ B=V_cD^2L,\ C=2V_fD^2(D-L),\ F=V_fLD^2$$

And:

$$\frac{\delta R}{\delta\rho_w}\ \frac{A(C\rho_w+B\rho_f)+AC(\rho_w-\rho_f)}{B\rho_f+(F+C)(\rho_w-\rho_f)}- \tag{13}$$

$$\frac{[AB\rho_f\rho_w+AC(\rho_w{}^2-\rho_f\rho_w)](F+C)}{[B\rho_f+(F+C)(\rho_w-\rho_f)]^2}$$

When: $\rho_w=\rho_f$ equations (12) and (13) reduce to:

$$R=\rho_fA=\rho_f\frac{D^2}{V_c}$$

And:

$$\frac{\delta R}{\delta\rho_w}=A\left(1=\frac{F}{B}\right)=\frac{D^2}{V_c}\left(1-\frac{V_f}{V_c}\right)$$

Therefore:

$$\left(\frac{1}{R_{4P}}\frac{\delta R_{4P}}{\delta\rho_w}\right)=\frac{1}{\rho_f}\left(1-\frac{V_f}{V_c}\right) \tag{14}$$

Next, we solve equation (10) for R as a function of ρ_w and obtain the following:

$$R=\frac{D^2V_f}{V_c{}^2}\left[\rho_w\frac{V_c}{V_f}-(\rho_w-\rho_f)\right] \tag{15}$$

And:

$$\frac{\delta R}{\delta\rho_w}=\frac{D^2}{V_c}\left(1-\frac{V_f}{V_c}\right)$$

When:

$\rho_w=\rho_f$ equation (15) reduces to:

$$R=\frac{\rho_fD^2}{V_c}$$

Then:

$$\left(\frac{1}{R_{2s}}\frac{\delta R_{2s}}{\delta\rho_w}\right)=\frac{1}{\rho_f}\left(1-\frac{V_f}{V_c}\right) \tag{16}$$

Comparing (16) with (14) we see that our requirement is satisfied.

It should be noted that in equations (2) through (11) the parameter V_c has been eliminated. This was done because the cell boundaries at the ends of the cells were not clearly defined owing to the different grid structures used. It was hoped that, by allowing this degree of freedom, the errors caused by this effect would be minimized.

APPENDIX C

Derivation and explanation of the relationship etween P_{fv} and P_{wv}:

To relate our results to the electrical conditions resent when the fish is not confined in a cell, we sed the following procedure:

In the four-body configuration, the power ensity in the water of R_4 is:

$$P_{wv}=\left(\frac{EE'}{E''}\right)^2 \frac{1}{\rho_w D^2} \qquad (1)$$

rom this:

$$\left(\frac{EE'}{E''}\right)^2 = P_{wv}\rho_w D^2 \qquad (2)$$

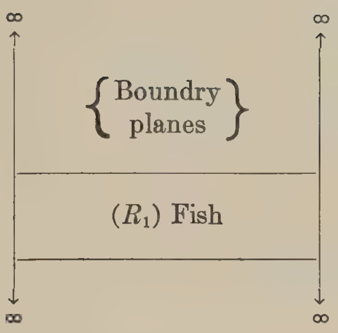
ubstituting this value into equation (9) of ppendix B and expanding V_c to infinity (the xpansion was carried out holding $\frac{D^2}{V_c}$ constant), e obtain the following result:

$$P_{wv}=P_{fv}\frac{\rho_f}{\rho_w}=\frac{V^2}{\rho_w}=\lim_{V_c\longrightarrow\infty} P_{wv}$$

r:

$$P_{wv}=\rho_f P_{fv}=V^2 \qquad (3)$$

By expanding V_c to infinity our volume conguration is as pictured below:



This illustration demonstrates the greatest weakness in our resolution model. That is, when we expand our configuration, our boundaries no longer enclose finite regions and therefore exhibit an impossible field condition. For correction of equation (3) and elimination of the effects of this property, it appears that it will be necessary to multiply (3) by some empirical function (f) of ρ_w and ρ_f.

Thus:

$$\rho_w P_{wv}=m^2\rho_f P_{fv}=V^2$$

Where:

$$m=f(\rho_w\rho_f)$$

This empirical function will have to be determined by further experimentation.

APPENDIX D

Tables A–1: How derived formulas were applied, and A–2: A sample of some of the numerical alues of ρ_f and P_{fv} that were obtained.

TABLE 1.—*Original measurement data*

Fish number	Polarity orientation	E' (volts)	E'' (volts)	E (volts)	I (μ amps)	P_w (ohm cm.)	Water temp. (° F.)	V_f (cc.)	D (cm.)	Date
a	Negative	2.3	3.18 2.77 2.37	1.70 1.48 1.30	80 70 60	29,250	47.0	15.3	15.8	1/5/59

TABLE 2.—*Calculation sample* (ρ_f)

Fish number	R_a (ohms)[1]	R (ohms)[1]	R_a-R (ohms)	L (cm.)[2]	$D-L$ (cm.)	A (×10¹¹)[3]	B (×10¹¹)[4]	$A-B$ (×10¹¹)	C (×10¹¹)[5]	ρ_f (ohm cm.)[6]
a	35000	20000	15000	11.6	4.20	1.24	0.675	0.565	12.72	1,244

[1] R_a and R (from graph)

[2] $L=1/3\ V_f+6.5$ (from graph)

[3] $A=R\ R_a V_f L$

[4] $B=2V_f R_a\ (R_a-R)\ (D-L)$

[5] $C=\rho_w L D^2\ (R_a-R)$

[6] $\rho_f=\frac{\rho_w(A-B)}{A-B+C}=\frac{(29{,}250)(.565)}{.565+12.72}=1{,}244$ ohm cm.

TABLE 3.—*Calculation sample* (P_{fv})

Fish number	E^2 (volts)[1]	D ($\times 10^5$)	G ($\times 10^{10}$)[2]	H ($\times 10^5$)[3]	$D-L$ (cm.)	$\rho_w - \rho_f$ (ohm cm.)	F ($\times 10^{-6}$)[4]	F^2 ($\times 10^{-12}$)	$L^2\rho_f$ ($\times 10^5$)	P_{fv} (μw)[5]
6a	1.54	4.62	10.55	10.71	4.20	28006	2.00	4.00	1.67	1.03

[1] $E_c^2 = \left(\frac{EE'}{E''}\right)^2$

[2] $G = \rho_f \rho_w D^2 L$

[3] $H = 2R_a V_f$

[4] $F = \frac{\rho_w D}{G + H(D-L)(\rho_w - \rho_f)}$

[5] $P_{fv} = (E_c^2)(F^2)(L^2\rho_f) = (1.54)(4.00)(1.67) = 1.03$

TABLE 4.—*A sample of the numerical values obtained for fish resistivity* (ρ_f) *and reaction power density* (P_{fv}) *using our derived equations*

Fish number	Polarity orientation (fish facing)	Water temp. (° F.)	Fish volume (cc.)	ρ_f (ohm cms.)	P_{fv} (μw/cc.)
1	−	49.0	5.9	1979	1.26
2	−	49.0	6.0	1446	1.19
3	+	49.0	5.3	1677	1.20
4	+	49.0	8.0	1092	0.94
5	+	49.5	6.1	1832	0.88
6	+	49.5	7.1	1119	1.00
7	−	49.0	9.0	1030	0.83
8	−	49.0	8.0	1000	0.50
9	−	49.0	6.5	1800	0.74
10	+	49.5	6.0	1470	0.96
11	+	49.5	6.2	790	1.39
12	−	49.5	5.4	1330	0.52

USE OF PLANT HEMAGGLUTININS IN SEROLOGICAL STUDIES OF CLUPEOID FISHES

By Carl Sindermann, *Fishery Biologist*

Bureau of Commercial Fisheries

ABSTRACT

As part of a general immunogenetic study of marine nimals, the use of hemagglutinins in seed extracts as been investigated. Individual variations were ound in reactions of alewife, blueback herring, and tlantic herring erythrocytes with certain extracts, articularly those of lima beans. Reactions of Atlantic herring cells with one lima bean extract paralleled those found with certain rabbit antisera. Evidence was obtained for heterogeneity among four spawning populations of alewives with quantitative tests of erythrocyte antigens using an extract of one variety of lima bean.

Plant extracts, particularly those of legume eeds, have been useful in differentiating human rythrocyte antigens (Boyd and Reguera, 1949; Makela, 1957; Boyd, Everhart, and McMaster, 958; Bird, 1959). This work has engendered nterest in possible use of such extracts for blood-rouping studies of other animal species (Bird, 953). The definitive separations of antigens ossible with plant extracts suggest that plant emagglutinins or lectins may prove useful in ystematic and racial studies of fish, as an adjunct o current immunogenetic studies using sera and ntisera of animal origin. Several laboratories re presently investigating the use of plant gglutinins in studies of teleosts, and Sprague 961) has reported their use in studies of oceanic kipjack.

This paper describes the use of selected plant emagglutinins to distinguish individual differ-nces within species of clupeoid fishes and to haracterize spawning populations of alewives.

METHODS

Blood samples were obtained from five species f clupeoid fishes (alewife, *Alosa pseudoharengus;* blueback herring, *Alosa aestivalis;* American shad, *Alosa sapidissima;* Atlantic herring, *Clupea harengus;* and Atlantic menhaden, *Brevoortia tyrannus*) taken in commercial trap nets at Belford, N.J., in April of 1960 and 1961. All fish were adults, although all species were not in the same condition of maturity in April. Blood samples from prespawning populations of alewives were obtained at Narragansett, R.I., in May, 1961; Bourne, Mass., in May, 1961; Damariscotta Mills, Maine, in May, 1961; and Tusket, Nova Scotia, in June, 1961. All samples were from upstream migrants, taken shortly after they had left the sea. Fish were bled by heart puncture with Pasteur pipettes. Whole-blood samples were refrigerated overnight, and serum decanted for other studies. Erythrocytes were washed from clots as needed, washed twice in 1.4 percent saline solution, and used in approximately 5 percent suspensions for testing.

Seeds from several species of Leguminosae were used: lima bean (*Phaseolus limensis*), lentil (*Lens culinaris*), and garbanzo bean (*Cicer arietinum*). Extracts were prepared by addition of 10 ml. of 1.4 percent saline to each gram of powdered seeds. After extraction for 3 hours at 37° C. and over-

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Note.—Approved for publication June 8, 1962.

night at 4° C. the mixture was filtered and centrifuged. The supernatant fluid (the extract) was frozen in 3 ml. aliquots until use.

Tube agglutination tests used 0.2 ml. extract dilution and 0.05 ml. cell suspension. Presence and degree of reaction were observed macroscopically after 1 hour incubation at room temperature and 30 seconds centrifugation. Results were recorded conventionally as (++++) complete agglutination, (+++) strong agglutination with a few large clumps, (++) moderate agglutination with numerous smaller clumps, (+) weak agglutination with many very small clumps, and (−) no agglutination. Cells were tested within 72 hours from the time the sample was taken.

Absorptions of extracts in an attempt to obtain specific reagents were carried out with washed cells. One part extract was added to one part packed cells. The mixture was shaken briefly to suspend the cells and incubated at room temperature for varying periods up to 2 hours. Absorbing cells were then settled by centrifugation, and the supernatant absorbed extract tested with a previously removed aliquot of the cells used for absorbing.

RESULTS

Individual Variations in Erythrocyte Antigens

A battery of extracts, including several varieties of lima beans, was used to determine whether individual differences could be detected among fish of each of the species studied. Tests with cells of 10 individuals from each of the five clupeoid species produced results shown in table 1.

Most of the extracts agglutinated herring cells, some extracts agglutinated alewife and blueback cells, only large lentil extract agglutinated menhaden cells, and none of the extracts agglutinated shad cells.

Several extracts gave sufficient distinction among individuals to suggest further study. Individual differences were detected in alewives, blueback herring, and Atlantic herring with hemagglutinins from lima bean varieties 5, 21, 92, 106, and 121, as well as large lentils. Lima bean variety 21, provided in quantity by J. A. Harding, University of California, was selected to determine the extent of individual differences in the three species. Twenty-five individual blood samples from each species were tested, and examples of results obtained are presented in table 2.

Using three doubling dilutions of lima bean variety 21 extract, some individuals were positive at all dilutions, while others were negative at the same dilutions. Most definitive separation of individuals occurred in Atlantic herring. Possible subtypes or dosage effects may be indicated by differences in reactivity of individual fish.

Reactions of Atlantic herring cells with extract 21 were similar to those with certain dilutions of a rabbit antiherring serum (GBH5R), as illustrated in table 3. Since rabbit antisera such as GBH5R have been sources of reagents for detection of erythrocyte antigens of herring, particularly the the C antigen (Sindermann and Mairs, 1959; Sindermann, 1961), the similarity of reactions suggested that certain extracts might be useful as substitutes for antisera. A comparison of 70 individual herring blood samples whose C antigens had been previously determined disclosed that C-negative fish were negative at all dilutions of extract 21 and that C-positive fish were all positive with extract 21.

TABLE 1.—*Reactions of erythrocytes from individual fish of five clupeoid species with seed extracts*

Seed extract	Cells																													
	Alewife										Blueback herring										American shad									
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Lima 121	+	+	++	+	+	+	++	+	++	−	−	−	++	−	−	+	−	+	+	−	−	−	−	−	−	−	−	−	−	−
106	−	−	+	−	−	−	++	−	+	−	−	−	+	−	−	+	−	++	+	−	−	−	−	−	−	−	−	−	−	−
128	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
75	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
5	+++	−	++	++	−	+	++	+	++	−	−	−	++	−	−	+	−	++	++	−	−	−	−	−	−	−	−	−	−	−
21	+	−	++	++	−	+	++	++	++	−	−	−	++	−	−	++	−	+	+	−	−	−	−	−	−	−	−	−	−	−
92	+	−	+	+	+	+	++	+	++	−	−	−	++	−	−	+	−	+	+	−	−	−	−	−	−	−	−	−	−	−
Garbanzo bean	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Large lentil	++	−	−	+	+	++	+	+	−	−	+	−	−	+	−	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−
Small lentil	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−

TABLE 1.—*Reactions of erythrocytes from individual fish of five clupeoid species with seed extracts*—Continued

Seed extract	Cells																			
	Atlantic menhaden										Atlantic herring									
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
ima 121	−	−	−	−	−	−	−	−	−	−	+++	++++	++++	++++	+++	++	+++	++++	−	++++
106	−	−	−	−	−	−	−	−	−	−	++	++++	++	++	+++	+++	++++	++	−	+++
128	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
75	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
5	−	−	−	−	−	−	−	−	−	−	++++	++++	++++	+++	++++	+++	++++	+++	−	+++
21	−	−	−	−	−	−	−	−	−	−	++++	+++	++++	+++	++++	+++	+++	++++	−	+++
92	−	−	−	−	−	−	−	−	−	−	+++	+++	++++	+++	+++	+++	++	++	−	+++
arbanzo bean	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
arge lentil	+	++	+	+++	+	+	++	+++	+	+	+++	++++	+++	+++	++++	++	+++	+++	−	+++
nall lentil	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−

ABLE 2.—*Examples of reactions of alewife, blueback herring, and Atlantic herring erythrocytes with three dilutions of lima bean variety 21*

Lima bean extract	Alewife cells									
	11	12	13	14	15	16	17	18	19	20
-undiluted	++	++	+	−	+++	++	−	++	++	−
1:1	+	+	−	−	++	++	−	++	+	−
1:2	+	−	−	−	++	−	−	++	+	−
	Blueback herring cells									
	11	12	13	14	15	16	17	18	19	20
-undiluted	+	+	−	−	+++	+++	+	−	+	−
1:1	−	+	−	−	++	++	+	−	−	−
1:2	−	−	−	−	++	+	−	−	−	−
	Atlantic herring cells									
	11	12	13	14	15	16	17	18	19	20
undiluted	++++	++++	+++	++++	−	++++	++++	++	++++	++++
1:1	+++	++++	+++	+++	−	++++	+++	+	++++	++++
1:2	+++	+++	++	+++	−	++++	+++	+	+++	+++

ABLE 3.—*Examples of reactions of Atlantic herring erythrocytes with plant hemagglutinins (extract 21) and rabbit antisera (GBH5R)*

Reagent	Atlantic herring cells									
	11	12	13	14	15	16	17	18	19	20
tract 21:										
1:1	+++	++++	+++	+++	−	++++	+++	+	++++	++++
1:2	+++	+++	++	+++	−	++++	+++	+	+++	+++
1:4	++	+++	++	++	−	+++	+	−	+++	++
bbit antiherring serum GBH5R):										
1:128	++++	++++	+++	++++	−	+++	+++	++	++++	+++
1:256	+++	+++	++	+++	−	+++	++	+	+++	++
1:512	+++	++	+	++	−	+	+	−	++	+

uantitative Studies of Agglutination Reactions in Alewife Spawning Populations

In view of the marked individual differences in actions of alewife erythrocytes with seed extracts, rticularly with lima bean variety 21, widely parated spawning populations were tested for actions with three dilutions of this extract (1:1, 2, 1:4). Numbers of fish negative at all dilutions and positive at all dilutions are presented in table 4. A scoring system comparable to that used by Race, Sanger, and Lehane (1953) and Ridgway, Cushing, and Durall (1958), involving addition of reaction scores of individual fish, was also used. Average scores for each spawning population are presented in figure 1. A test for independence of scores (Snedecor, 1956), pooling

Table 4.—*Individual reactions of alewives from four spawning populations with lima bean variety 21 extract*

Location	Number sampled	Number positive at all dilutions	Number negative at all dilutions
Narragansett, R.I.	200	64 (32%)	66 (33%)
Bourne, Mass.	200	112 (56%)	28 (14%)
Damariscotta Mills, Maine	190	7 (4%)	112 (59%)
Tusket, Nova Scotia	73	12 (16%)	33 (45%)

frequencies of test scores of six and more (table 5) indicated that the distribution of scores was dependent on the population studied (chi square$=$180.2, d.f.$=$18, $p<.001$). Only four out of many possible spawning populations were sampled, and a more definitive picture of the discreteness of spawning groups may emerge as more populations are studied.

Table 5.—*Frequencies of agglutination scores in four alewife spawning populations*

Scores	Numbers of fish				
	Tusket, Nova Scotia	Damariscotta Mills, Maine	Bourne, Mass.	Narragansett, R.I.	Total
0	33	112	28	66	239
1	15	41	17	27	100
2	11	22	31	30	94
3	3	6	15	22	46
4	1	7	20	14	42
5	6	1	44	15	66
6 or more	4	1	45	26	76
Total	73	190	200	200	663

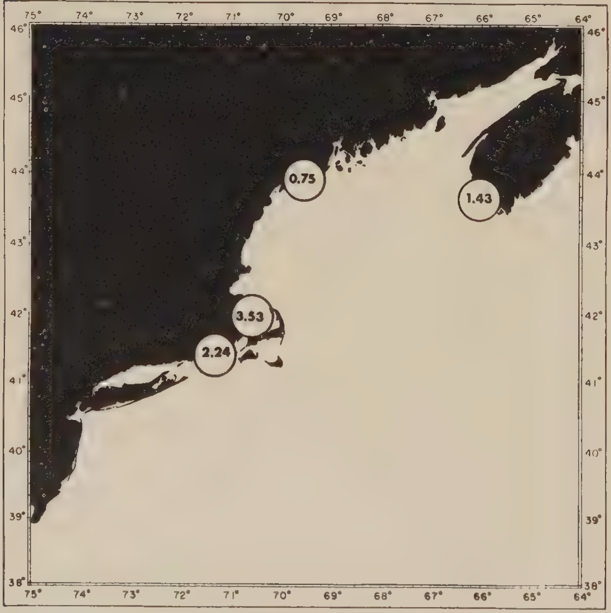

Figure 1.—Average reaction scores of four alewife spawning populations with lima bean variety 21 extract.

DISCUSSION

Immunogenetic studies of fishes have advanced rapidly during the past decade, so that quantitative information has already accumulated for subpopulations of several species (Ridgway, Cushing, and Durall, 1958; Sindermann and Mairs, 1959; Suzuki, Morio, and Mimoto, 1959). There must be, however, continuous exploration of new techniques, even as quantitive studies proceed, since adequate serological characterization of subpopulations depends on description and use of several different factors or blood-group antigens. An examination of the possible utility of plant hemagglutinins in serological research constitutes a phase of such exploratory work.

It is premature to attempt genetic explanations for the results of the present work, but the fact that reactions of clupeoid erythrocytes with certain extracts paralleled those obtained with specific rabbit antisera suggests that discrete antigenic factors are involved in the agglutinations. Also, the distributions of reaction scores for several alewife spawning populations lacked the continuous gradation characteristic of polygenic inheritance, but resembled distributions obtained with a series of alleles at a single locus. Individual differences in clupeoid species have been recognized, and this is significant, but information from fractionation of extracts, or from study of known crosses, should precede proposals of genetic systems that may control such differences.

There are advantages and difficulties in the use of plant extracts. Many varieties of many species of plants may be tested, relatively easily and inexpensively. Once a satisfactory variety has been found, any desired amount of extract may be prepared, whereas the amounts of specific antisera are dependent on the blood volume of the experimental animal used. Specific reagents for detection of individual antigenic variation are usually derived from absorptions of sera or antisera. Plant extracts have thus far proved resistant to normal methods of absorption with clupeoid fish cells. Use of unabsorbed extracts may provide valuable information, but further attempts to refine the extracts as reagents should be carried out. Also, the nature of the reaction between animal erythrocyte and extract that produces often highly specific agglutination is poorly

nderstood, and requires further study. Despite
ich limitations, plant hemagglutinins offer a
romising approach to recognition and character-
ation of subpopulations of fishes. Plant extracts
an form part of a wide spectrum of serological
ools available to fishery research.

SUMMARY

Erythrocytes of the five dominant clupeoid
oecies of the western North Atlantic: alewife
Alosa pseudoharengus*), blueback herring (*Alosa
stivalis*), American shad (*Alosa sapidissima*),
tlantic menhaden (*Brevoortia tyrannus*), and
tlantic herring (*Clupea harengus*) were studied
r reactivity with plant extracts. Individual
ariations were found in reactions of alewife,
ueback herring, and Atlantic herring erythro-
tes with hemagglutinins present in seed extracts.
veral varieties of lima beans provided clear
fferentiation of individuals. Evidence for pop-
ation heterogeneity was obtained when blood
mples from four spawning populations of alewives
ere tested against an extract of one variety of
na bean.

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ans of variety 21 for this work. Personnel of
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arch Board of Canada, and the Fisheries Board
Canada assisted in collection of some of the
ood samples.

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ME ASPECTS OF THE OCEANOGRAPHY OF LITTLE PORT WALTER ESTUARY, BARANOF ISLAND, ALASKA

CHARLES F. POWERS, *Associate Research Oceanographer,* Institute of Science and Technology, Great Lakes Research Division, University of Michigan

ABSTRACT

connection with studies on the survival of the pink on, *Oncorhynchus gorbuscha,* certain aspects of oceanography of Little Port Walter estuary were stigated. Efforts were directed principally toward lies of the patterns and mechanisms of circulation; er exchange; flushing; and temporal and spatial ribution of salinity, temperature, transparency, and olved oxygen.

shallow sill separates the estuary into two basins, innermost possessing the structural and three-red circulatory characteristics of a fiord. A net ay movement of intermediate and deep water re-nded to a salt pump activated by the inflow from the ary's single tributary stream, Sashin Creek. The rate of pumping increased materially during periods of heavy precipitation. The pattern of circulation in a shallow top layer containing the fresh water was strongly affected by the discharge from Sashin Creek but was not greatly affected by winds, since the estuary is well sheltered.

The average flushing time for the fresh water of the inner basin, computed by the method of Ketchum, Redfield, and Ayers (1951), showed a correlation with the rate of stream discharge: flushing time decreased as stream discharge increased. The total water exchange between the inner and outer basins varied in magnitude with the monthly tide range and fresh water runoff and showed some response to wind.

uring the spring and summer of 1959, studies e made of certain aspects of the oceanography he estuary of Little Port Walter, Alaska. se studies were supported by the Bureau of mercial Fisheries and were based at the ogical Field Station at Little Port Walter. y constituted part of a series of investigations the biology of pink salmon, *Oncorhynchus uscha.* Little Port Walter estuary is the of an annual spawning run of this commercially ortant species, and knowledge of environtal conditions within the estuary is pertinent vestigations of their biology.

he oceanographic studies were designed to in information on the following: spatial ribution of temperature and salinity, at high and low tides, under various conditions of freshwater runoff; temporal distribution of temperature, salinity, dissolved oxygen, and transparency at selected reference stations; circulation and flushing of the estuary and the relation of these factors to the discharge of Sashin Creek; and total water transport into and out of the estuary. The methods of studying these various features and parameters are presented in the discussion of methods of investigation and observation.

We were not equipped to operate in adjacent large open waters, although observations there would have been desirable and helpful. Work was therefore limited to the estuary.

The estuary is located near the tip of Baranof Island in southeastern Alaska, about 40 airline miles from Sitka. A stream, Sashin Creek, enters the inner end over a small waterfall which

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tribution No. 7, Great Lakes Research Division, Institute of Science echnology, University of Michigan, Ann Arbor, Mich.

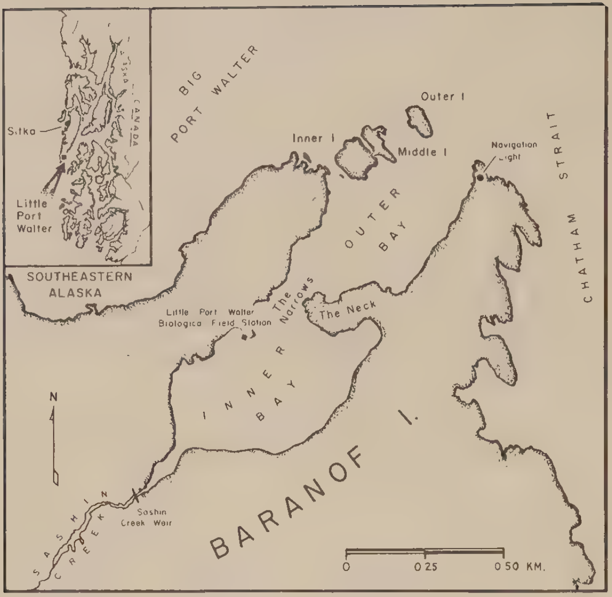

FIGURE 1.—Little Port Walter estuary, Baranof Island, southeastern Alaska.

marks the limit of salt-water intrusion. At its seaward end the estuary connects with Chatham Strait and Port Walter Bay (fig. 1).

The distance from the waterfall to Chatham Strait is 1.5 kilometers (km.); the distance across the widest part of the estuary is about 0.4 kilometer (km.). A peninsula, The Neck, extends from the south shore and divides the estuary into two bays of approximately equal area, Inner Bay and Outer Bay. These are connected by a short channel, the Narrows, between The Neck and the north shore.

The maximum observed depth of Inner Bay was 21 meters (m.) and of Outer Bay, 44 m. (referred to mean lower low water).[1] The depth at The Narrows, where a shallow sill is present, was almost 5 m. Because of this sill, Inner Bay has the structural characteristics of a fiord; Outer Bay does not, since it connects directly with Chatham Strait through a channel approximately 36 m. deep.

Three small rocky islands partially separate Outer Bay from Port Walter Bay to the north. Proceeding in a seaward direction, they are Inner, Middle, and Outer Islands. Three shallow channels connect with Port Walter Bay, but the channel between Inner and Middle Islands floods only during spring tides and has no functiona significance.

The basins of both Inner and Outer Bays ar steep sided, with practically no shelf formatio except for a small shoal area at the head of Inne Bay. The surface area of the estuary consequently undergoes little change between low and higl waters. Basins of this type are characteristi of Baranof Island as well as much of the rest o southeastern Alaska. The coastline is frequentl indented by long narrow, deep embayments fron which mountains rise sharply to heights of severa thousand feet.

Tides in the estuary exhibit the exaggerate diurnal inequality typical of the west coast o North America. The range of spring tides a Little Port Walter was as much as 4.6 m., th range of neap tides less than half of this. Withi the estuary the tide has the characteristics of standing wave, with high and low slack water occurring at about the same time over the entir basin.

The coastal region of southeastern Alaska i a zone of heavy precipitation. Little Port Walte receives an average of 221 inches per year.

John C. Ayers gave much valuable advic during the writing of this paper.

METHODS OF INVESTIGATION AND OBSERVATION

CRUISES

Five cruises were conducted to obtain basic oceanographic data over the entire estuary during different conditions of fresh-water runoff. Cruises were made at slack before ebb plus or minus one-half hour and at slack before flood plus or minus one-half hour. Eighty-nine stations were occupied during three cruises at slack before ebb, and 62 during two cruises at slack before flood. Station positions (fig. 2) were the same for all five cruises except where indicated. To show the stage of tide on which a particular cruise was conducted, cruise numbers bear the prefix "H" for slack before ebb and "L" for slack before flood. During each daily cruise period, as many stations as possible were visited at both slacks so that "H" and "L" cruises bearing the same number were conducted during the same time interval. Cruises H–1 and L–1 were made between June 25 and July 2, cruise H–2 between July 7 and 29,

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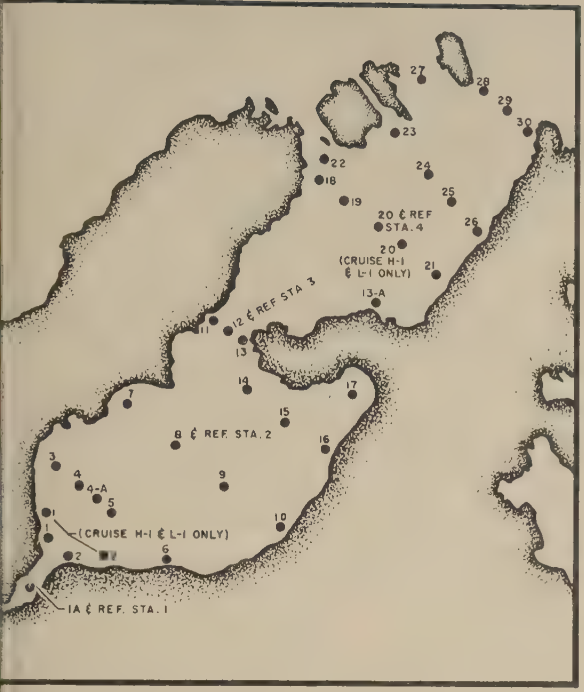
[1] In this discussion, all depths to bottom are referred to the datum of the U.S. Coast and Geodetic Survey: mean lower low water (U.S. Coast and Geodetic Survey, 1959).



URE 2.—Numbered stations for study of Little Port Valter estuary. Except where indicated, numbers refer o stations of cruises H–1, L–1, H–2, H–3, and L–3.

cruises H–3 and L–3 between July 29 and gust 4. Cruise L–2 was missed because of ries of boat engine failures. Cruise H–2 ended en about two-thirds completed because of idly changing conditions in the estuary, ught on by heavy rains.

t each of the 151 stations water samples for nity determinations were obtained by Kem-rer bottle at selected depths, temperature was ermined by bathythermograph, transparency measured by white Secchi disk, and wind ed and direction and weather conditions were orded. Wind speed was estimated, according he Beaufort scale, from the condition of the er surface; whereas direction was estimated reference to the geographical orientation of the of the estuary. Salinity was determined in laboratory at the field station by hydrometry, the results expressed in grams per kilogram rts per thousand: ‰). Data from the cruise ions are on file at the laboratory at the Little t Walter Field Station.

ANCHOR STATIONS

n addition to the stations included in the five ises, anchor stations were occupied in The Narrows, in the two functional channels between Outer Bay and Port Walter Bay, and in the entrance to Chatham Strait. These stations furnished data on current profiles and water transport. At anchor stations hourly determinations of the current profile from surface to bottom were obtained throughout the complete tidal cycle with a von Arx current meter (von Arx, 1950). With each lowering of the meter, water samples, temperature determinations, and wind and weather observations were obtained in the same manner as described for cruise stations.

Data from all anchor stations are on file at the station laboratory.

REFERENCE STATIONS

To obtain knowledge of temporal changes in the parameters studied, four reference stations (fig. 2) were occupied each week. Stations 1 and 2 were located in Inner Bay—station 1 just below the mouth of Sashin Creek and station 2 in the deep part of Inner Bay. Station 3 was over the sill in The Narrows. The three stations were occupied on April 3 and thereafter at intervals of approximately 1 week until August 21. Salinity, temperature (by resistance thermometer), and transparency were determined, and wind and weather were noted. Dissolved oxygen was measured on June 6, and weekly from July 11 to August 21 at stations 2 and 3 only. On July 11 reference station 4 was added. Located in the center of Outer Bay at the deepest part, it was occupied weekly until August 21. The observations were the same as those made at stations 2 and 3, except that transparency was not measured, and temperature was measured by a bathythermograph which was calibrated against the resistance thermometer. Reference stations were always visited at slack before ebb, plus or minus one-half hour. The remaining data are on file at the station laboratory.

MEASURING RUNOFF

Except during periods of intense precipitation, the entire fresh-water runoff into the bay was from Sashin Creek. This stream was not gaged, but it was possible to estimate its volume of flow. From early spring until July 20, the stream was dammed near its mouth by a fish weir with two rectangular spillways. A recording gage continuously monitored the level of the water impounded by the weir. The gage record gave the head of water

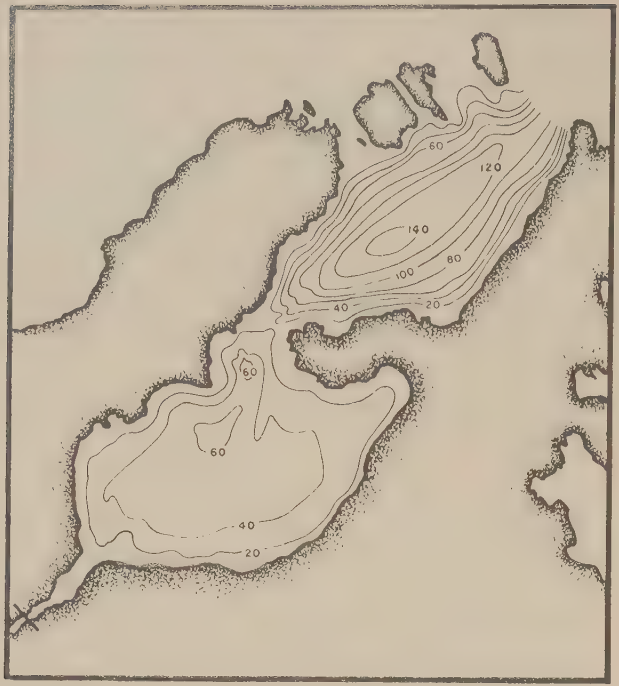


Figure 3.—Bathymetry in feet of Little Port Walter estuary, based on sonic soundings corrected to datum.

over the spillways, and from this the velocity of effluent through the spillways was computed by:

$$v=\sqrt{2gh}$$

where g was the acceleration due to gravity and h the head of water. Multiplying the velocity of effluent by the cross-sectional area of the spillways gave the volume of flow.

After the dam was removed on July 20, volume of flow was calculated by the method of Robins and Crawford (1954), utilizing cross-sectional area and timed observations of floats where the stream flowed through the open weir.

BATHYMETRY

Since navigation charts give only a sketchy bathymetry of the estuary a bathymetric chart was constructed (fig. 3). Sounding transects were made with a battery-powered portable recording echo sounder by running the boat at constant speed from one side of the estuary to the other between objects on shore whose positions were charted. Depths were corrected to datum before contouring, using predicted water levels for the days when the sounding operations were made (U.S. Coast and Geodetic Survey, 1959). These corrections are only approximate, their accuracy being limited by differences that may have existed between predicted and actual water levels.

METEOROLOGY

Meteorological data collected daily at Little Port Walter were maximum and minimum air temperatures and precipitation. These data, along with daily observed maximum and minimum temperatures of Sashin Creek, are presented graphically in figure 4.

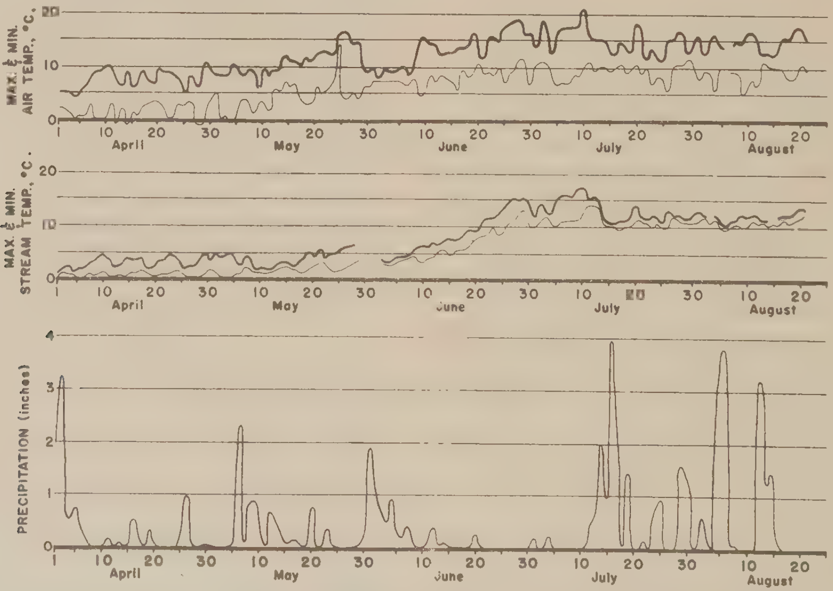


Figure 4.—Regimes of air temperature, stream temperature, and precipitation at Little Port Walter, April 1 to August 21, 1959.

ir temperature was measured with a sheltered ss-mercury maximum-minimum thermometer ated near the station laboratory on Inner Bay. nperature of the creek was taken daily just ve the weir with a stem thermometer at approx- tely 0800 and1800 hours. Rainfall was meas- l with a standard U.S. Weather Bureau rain e located near the laboratory.

outine meteorological observations at the oratory did not include wind conditions, they were recorded at all stations and are file at the station laboratory. Wind con- ons for the five cruises and the concurrent cipitation regimes are shown in table 1. Veloc-

LE 1.—*Meteorological observations on five cruises in Little Port Walter estuary*

uise number and date	Station	Average wind direction and force	Precipitation (inches)
1959			
une 25	1A–7	Calm to SW.–1	0
une 26	16	Calm	0
une 27	11–15, 17	Calm	0
une 30	19–21	NE.–1	0
uly 1	18, 22–24, 26	NE.–1	0. 20
uly 2	25, 27–30	Calm to SW.–1	0
uly 27	1A–7	Calm	0. 01
uly 28	8–18, 21, 22	SE.–1 to SW.–1, 2	0. 05
uly 29	19, 20	Calm	1. 57
uly 30	1A–6	Calm	1. 43
uly 31	7–10, 15	E. to SE.–1	0. 03
uly 31	16, 17	NW.–1	...
ug. 1	11–14	Calm to SSW.–2	0. 04
ug. 1	18, 21, 22	Calm to W.–1	...
ug. 2	19, 20, 23, 26	Calm	0. 60
ug. 3	24	E.–2	0. 27
ug. 4	25, 27–30	W.–1, 2	0. 01
une 25	1A–10	SE.–1, 2	0
une 26	11, 12	NNE.–1, 2	0
une 26	13–17	Calm to SE.–1	...
une 30	18–21	NE.–1, 2	0
uly 1	26–30	SW.–1, 2	0
uly 29	1A–7	Calm	1. 57
uly 30	8–10, 15, 16	SE.–1, 2	1. 43
uly 30	17	NW.–2	...
uly 31	11–13	SW.–1	0. 03
uly 31	14, 18, 21, 22	Calm	...
ug. 1	13A, 19, 20	Calm to W.–1	0. 04
ug. 2	23–26	E.–1	0. 60
ug. 3	27–30	W.–2	0. 27

s during the five cruises never exceeded ufort force 2, and, except for cruise L–1, at t the inner half of Inner Bay was always ted during periods of calm. No pronounced erences in distributions of temperature or nity as a result of variations in wind direction e observed.

DROGUES AND DRIFT BOTTLES

irect observations of surface current directions e made in Inner Bay with "drift bottles" 2-foot-square (0.6 m.²) sheet metal current drogues suspended from gallon glass jugs. The drift bottles were actually 1-pint motor oil cans ballasted with sand so that they floated nearly submerged.

OBSERVATIONS

SALINITY

Surface Salinity at Slack before Ebb

The lowest salinity in Inner Bay was generally found at the mouth of Sashin Creek, although during cruise H–2 it was found at station 17 in the small cove at The Neck. In cruises H–1 and H–3 (figs. 5 and 6) this freshened water showed a definite tendency to hold toward the north shore. This tendency was not as noticeable during cruise H–2 (fig. 7), probably as a result of reduced outflow of the stream at that time. Wind was not a causative factor in this distribution, since in all three "H" cruises the upper part of Inner Bay was visited during periods of calm.

The most prominent feature of the surface salinity in Inner Bay during cruises H–1 and H–3 was a large eddylike configuration of isohalines in the southeast quadrant (figs. 5 and 6). Salinity values on the side of the eddy toward the middle of the bay were continuous with those observed in The

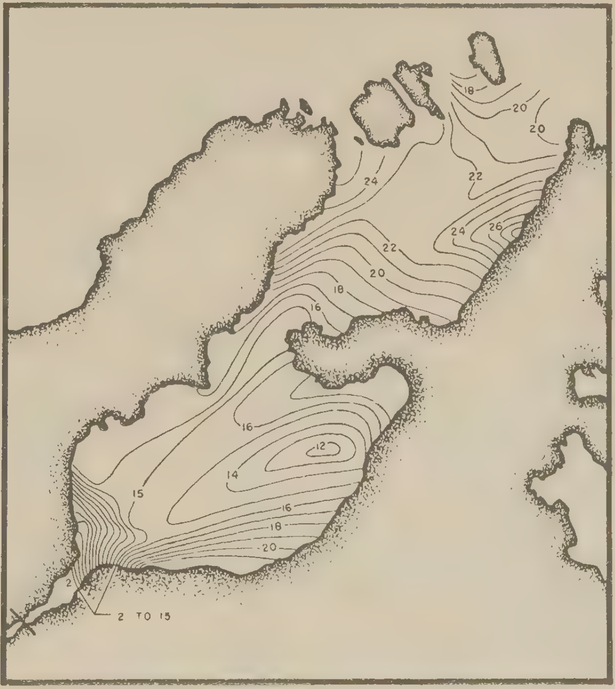


FIGURE 5.—Surface salinity; ‰, slack before ebb. Cruise H–1, June 25 to July 2.

Narrows. During cruise H–2 the eddylike structure was not present, but a series of recurved isohalines bent around The Neck from The Narrows into Inner Bay (fig. 7).

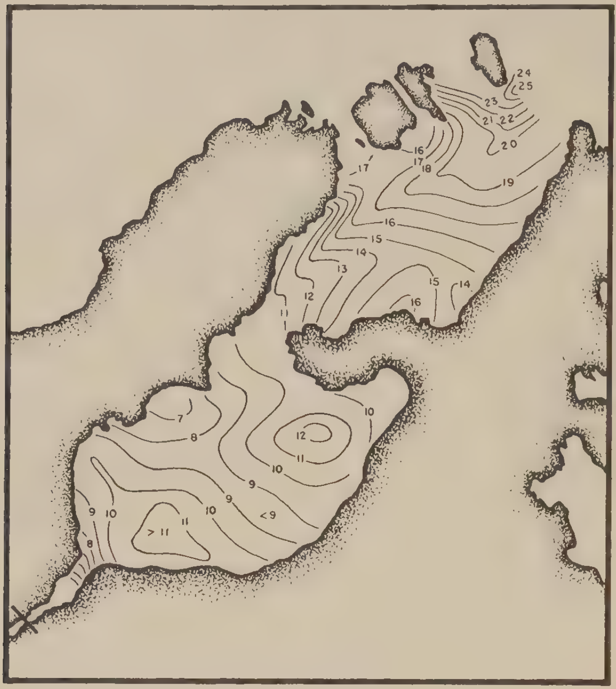


FIGURE 6.—Surface salinity; °/oo, slack before ebb. Cruise H–3, July 30 to August 4.

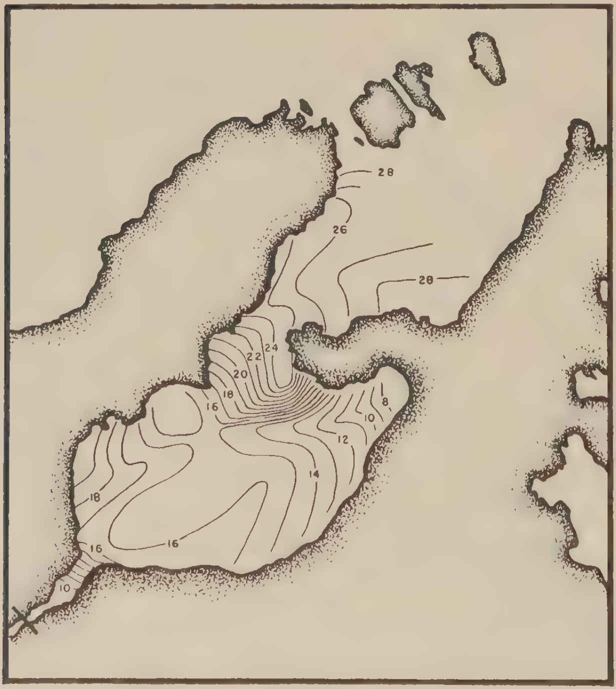


FIGURE 7.—Surface salinity; °/oo, slack before ebb. Cruise H–2, July 27–29.

Although salinity was low at the head of Inner Bay along the north shore, it was relatively high in a comparable position on the south shore and did not appear to be appreciably affected by the direct outflow of the stream (figs. 5, 6, and 7).

During all three cruises isohalines in Outer Bay tended to parallel the north shore between the mainland-Inner Island channel and The Narrows (figs. 5, 6, and 7). Over the rest of Outer Bay, salinity tended to increase in the direction of Chatham Strait, with generally higher values in the southern portion.

Surface salinity in Outer Bay was generally higher than in Inner Bay. Average surface values for the three cruises at slack before ebb were as follows:

	Inner Bay	*Outer Bay*
Cruise H–1	14. 2	22. 0
Cruise H–2	15. 0	27. 4
Cruise H–3	10. 1	18. 3

The notably lower average values of surface salinity observed during cruise H–3, as compared with the previous cruises, appeared to reflect prevailing precipitation regimes. Cruise H–1 was begun June 25 and ended July 2. Precipitation was extremely low during that period, with the only measurable amount (0.20 inch) recorded July 1.

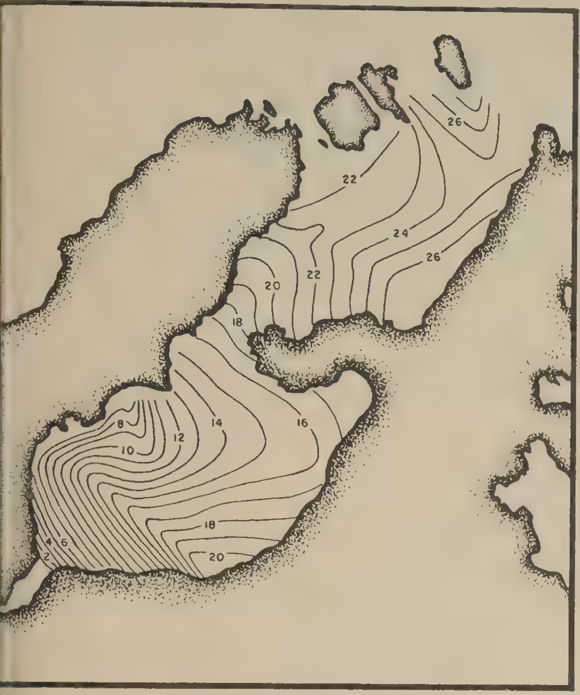
Cruise H–2 was carried out on July 27 and 28 and the morning of the 29th. Precipitation was negligible, although 1.57 inches of rain fell on the 29th after the cruise was terminated.

Cruise H–3 was begun July 30 and completed August 4. Precipitation was only slightly less on July 30 (1.43 inches) than on the 29th. During the remainder of the cruise it varied between 0.03 inch on July 31 and 0.60 inch on August 2. The heavy rains of July 29 and 30, however, appeared to be sufficient to greatly reduce surface salinity throughout the cruise.

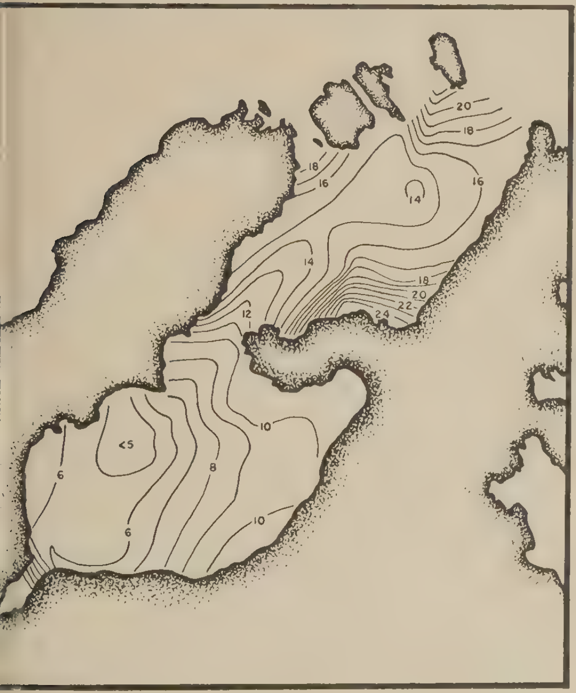
Surface Salinity at Slack before Flood

Stations at slack before flood were occupied during cruises L–1 and L–3.

The lowest salinity of Inner Bay was found during cruises L–1 and L–3 at the head of the estuary where the fresh water from Sashin Creek entered. It remained low along the north shore for about two-thirds of the distance to The Narrows (figs. 8 and 9). From that point, it increased both oss and down the bay. In cruise L–3 (fig. 9), alines within this ascendant exhibited definite protrusions toward the cove at The Neck and toward The Narrows. Such protrusions were present, but less pronounced, in cruise L–1 (fig. 8). Near the south shore, just downbay from the shoal at the head of the bay, isohalines bent sharply and extended past the middle of the bay in the direction of the opposite shore (figs. 8 and 9).



IGURE 8.—Surface salinity; °/₀₀, slack before flood. ise L–1, June 25 to July 2.



GURE 9.—Surface salinity; °/₀₀, slack before flood. se L–3, July 30 to August 4.

On both cruises, the downbay increase in salinity observed in Inner Bay continued through The Narrows and into Outer Bay as a seaward-protruding tongue of isohalines. In Outer Bay this tongue occupied the north half of the bay as far as Inner Island. The south side of the tongue was continuous with a crossbay ascendant which attained maximum values in the embayment on the seaward side of The Neck.

Seaward of Middle Island, salinity increased rapidly to the end of the bay.

Average surface salinity at slack before flood was consistently greater in Outer Bay.

Values for cruises L–1 and L–3 were as follows:

	Inner Bay	*Outer Bay*
Cruise L–1	13. 8	24. 3
Cruise L–3	6. 8	17. 9

The greatly lowered average surface salinity of cruise L–3 was similar to the lowering observed during cruise H–3 and again appeared to reflect the effects of the heavy rains of July 29 and 30.

Vertical Salinity Distribution during Cruises at Slack before Ebb

Salinity along the axis of the estuary, as observed at slack before ebb during cruises H–1, H–2, and H–3 (figs. 10, 11, and 12), was strongly stratified. In Inner Bay, water of less than 30°/₀₀ was usually found in the upper 2 m. and never below a depth of 5 m. At greater depths the salinity was nearly constant, varying only between 30 and 32°/₀₀.

In Outer Bay stratification was generally less intense than in Inner Bay. The 30 and 31°/₀₀ isohalines rose from depths of about 20 and 30 m. in Outer Bay to about 5 m. in Inner Bay on cruise H–1. During cruise H–3, the 30°/₀₀ isohaline was near the surface over the entire estuary, but the 31°/₀₀ isohaline rose from about 35 m. in Outer Bay to less than 5 m. at the head of Inner Bay.

At depths below the superficial top layer, vertical salinity distribution at slack before flood differed little from that at slack before ebb and is not discussed here.

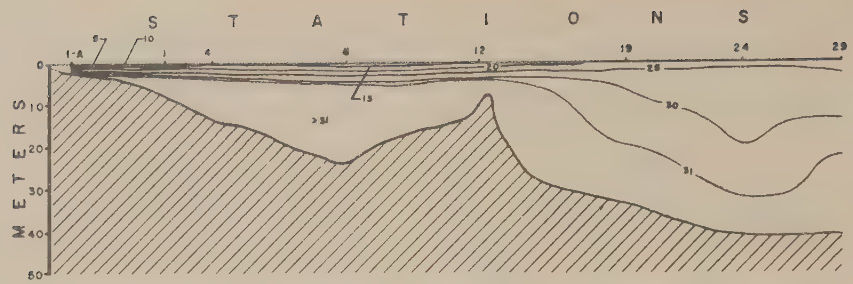


Figure 10.—Vertical distribution of salinity; °/₀₀, along longitudinal axis of estuary at slack before ebb. Cruise H–1, June 25 to July 2. (Data of station 8 missing.)

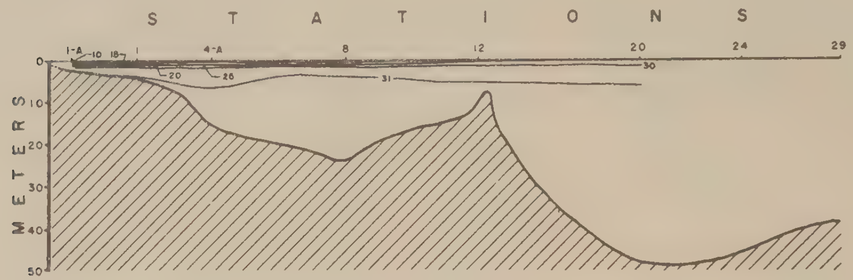


Figure 11.—Vertical distribution of salinity; °/₀₀, along longitudinal axis of estuary at slack before ebb. Cruise H–2, July 27–29.

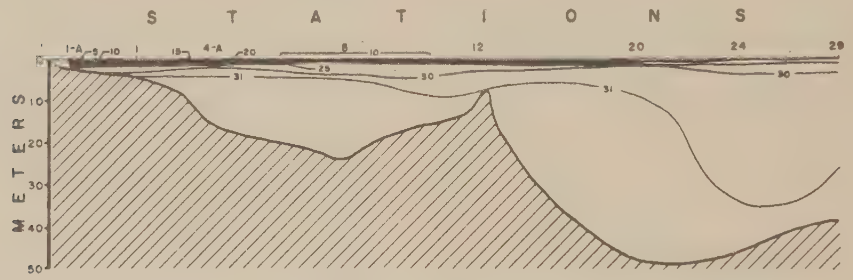


Figure 12.—Vertical distribution of salinity; °/₀₀, along longitudinal axis of estuary at slack before ebb. Cruise H–3, July 30 to August 4.

Temporal Salinity Distribution

The temporal variation of salinity for Inner Bay, as observed at reference station 2 between April 3 and August 21, and daily precipitation for the period are shown in figure 13.

A strong halocline lay between the surface and 1 m. throughout most of the observation period. It was notably weakened between April 24 and May 22, probably by the mixing effects of a northeastern storm which began on April 28 and continued into the first week of May. Winds during this period attained velocities estimated at Beaufort force 6 to 7. Although heavy rains began on May 6 and continued intermittently until May 24, they or the associated heavy runoff from Sashin Creek were probably not the cause of the partial breakdown of the halocline, which remained strongly intact during prolonged periods of much heavier precipitation during July and August. A comparison of precipitation and surface salinity (fig. 13) shows that surface salinity lowered appreciably with heavy rainfall. The effect of the increased fresh-water input always appeared to be restricted to a superficial surface layer. Most of the column was consistently of salinity of 30°/₀₀ or more.

TEMPERATURE

Surface Temperature at Slack before Ebb

During cruise H–1 (fig. 14), water of > 12.5° C. protruded sharply into the southeastern quarter of Outer Bay from Chatham Strait. This extension reached to station 25, where temperatures decreased slightly to a low of < 11° C. at The

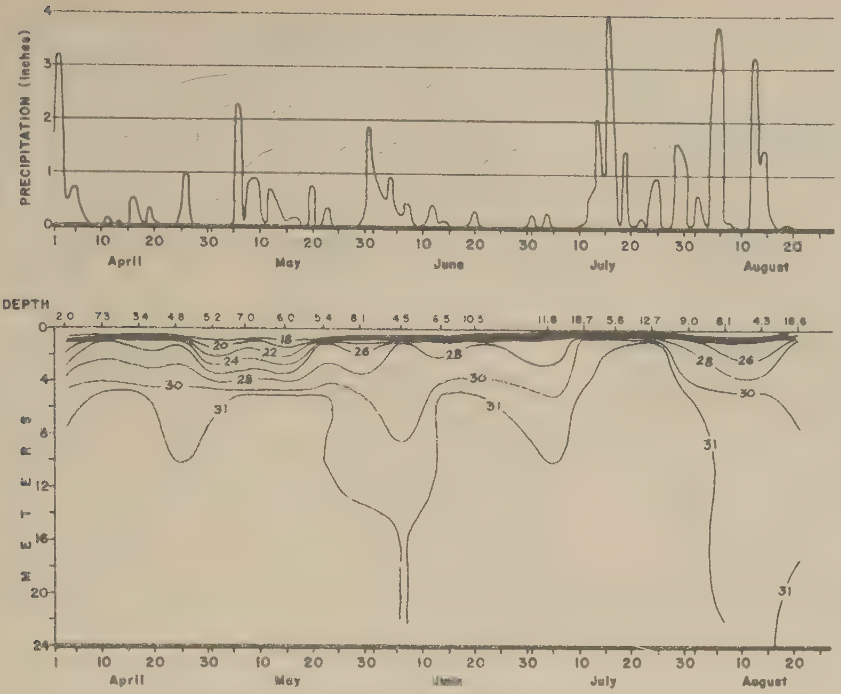


FIGURE 13.—Upper: Daily precipitation (inches of rainfall) at Little Port Walter, April 1 to August 21, 1959. Lower: Temporal sequence of salinity, °/₀₀, at reference station 2, April 3 to August 21, 1959. Contours representing values less than 18 °/₀₀ are omitted. Numbers at top are observed surface salinities.

12.5
12
12.5
11.5
10.5
10.5
10.5
11.5
12
11.5
12.5

URE 14.—Surface temperature, degrees C., slack before ebb, cruise H–1, June 25 to July 2.

Neck. Water of < 11° C. extended through The Narrows into the outer end of Inner Bay, then gradually warmed toward the head of the bay. Maximum temperatures in Inner Bay (> 12.5° C.) occurred as a narrow tongue extending from station 2 to station 4. Temperatures fell to < 11° C. at the mouth of Sashin Creek.

In cruise H–2 (fig. 15) a tongue of < 11° C. water extended into The Narrows from Outer Bay. This tongue was separated from the north shore by > 11° C. water that extended from the mainland-Inner Island channel into The Narrows. Slightly cooler surface waters characterized most of Inner Bay, with lows of < 10° C. in the cove at The Neck and in a narrow band in the northwest quadrant.

The nearest approach to homogeneity of surface temperatures was observed on cruise H–3 (fig. 16). The greater part of Outer Bay was occupied by water of > 10.5° C. Along the north shore a narrow band of < 10.5° C. water extended from the mainland-Inner Island channel through The Narrows, and a wider band of like temperature extended along The Neck and through The

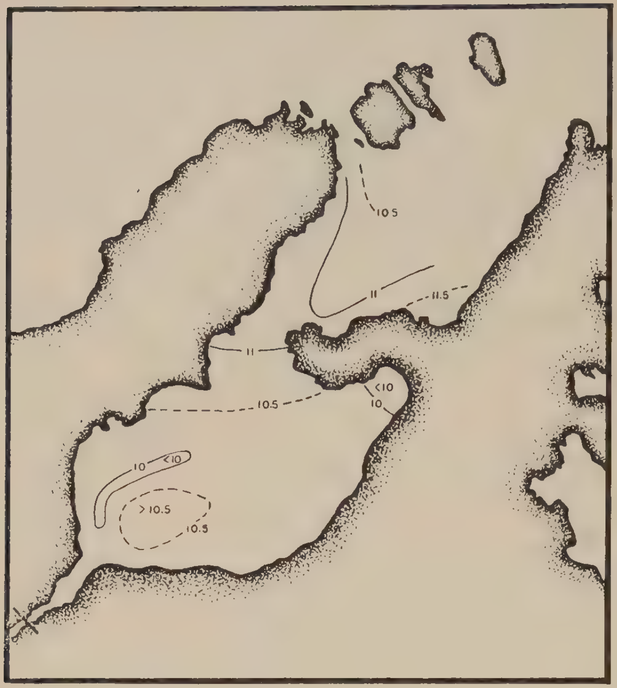


FIGURE 15.—Surface temperature, degrees C., slack before ebb, cruise H–2, July 27–29.

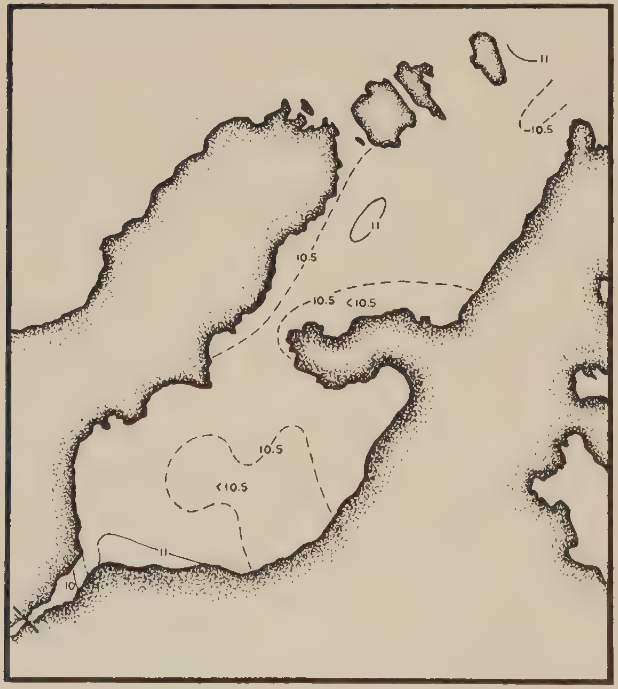


FIGURE 16.—Surface temperature, degrees C., slack before ebb, cruise H–3, July 30 to August 4.

Narrows. The < 10.5° C. water continued through The Narrows from Outer Bay and occupied a large part of Inner Bay. A large bilobed area of < 10.5° C. water protruded from the south shore. Temperatures of > 11° C lay over the shoal at the head of the bay; at the mouth of the stream they decreased to < 10° C.

Surface Temperature at Slack before Flood

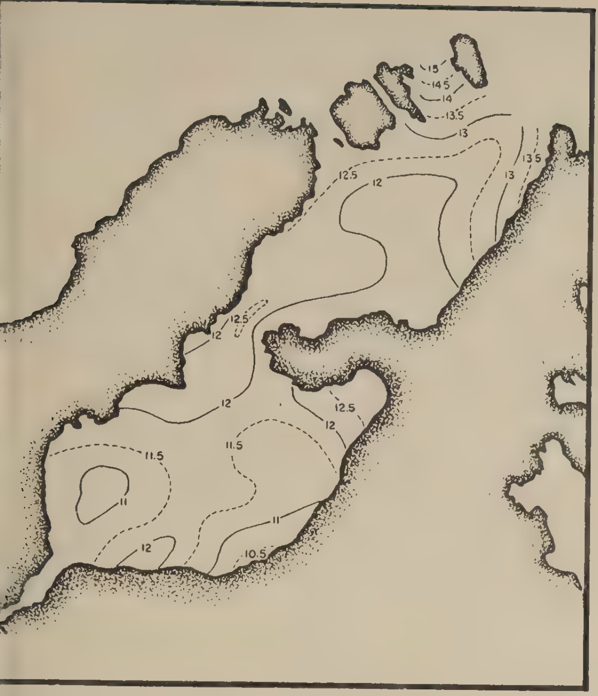
During cruise L–1 (fig. 17) a fairly large mass of <11.5° C. water extended from the mouth of Sashin Creek to the northwest quarter of Inner Bay. The southern half of Inner Bay was occupied by a small body of >12° C. water that surrounded station 6 and an adjacent area of <11.5° to <10.5° C. water that reached to the cove at The Neck, where it warmed to >12.5° C. A band of >12° C. water extended from the vicinity of station 7 near the north shore, through the south side of The Narrows, and into Outer Bay where it turned back toward the north shore. It then protruded in a downbay tongue to station 24 where it recurved to the south to terminate at the south shore near station 22. The tonguelike formation was continued to the center of the Outer Island-Light Point passage by the 12.5° and 13° C. isotherms. Warmer water lay on either side of this tongue; temperature was >13.5° C. along the south shore, and increased to 15° C. in the Middle Island-Outer Island channel.

Surface temperature structure during cruise L–3 (fig. 18) was much less complex than during cruise L–1. A large eddylike structure of >11° C. water lay in the southern half of Inner Bay, and >11° C. water was also found along the north shore. Water of <11° C. ran in a wide band from the head of the bay to and through The Narrows and also extended along shore through the southern half of Inner Bay to completely surround the eddy of >11° C. water.

From The Narrows the band of <11° C. water reached to Chatham Strait. It was partially separated from the north shore by a narrow band of <10.5° C. water that lay between The Narrows and the Mainland-Inner Island channel. In the southern half of the bay the extent of the <11° C. water was interrupted by a tongue of >11° C. water that ran from The Neck to the center of the bay, and by a cooler area of <10.5° C. water between Light Point and Inner Island.

Vertical Temperature Distribution during Cruises at Slack before Ebb

Vertical distribution of temperature along the central axis of the estuary at slack before ebb



GURE 17.—Surface temperature, degrees C., slack before flood, cruise L–1, June 25 to July 2.

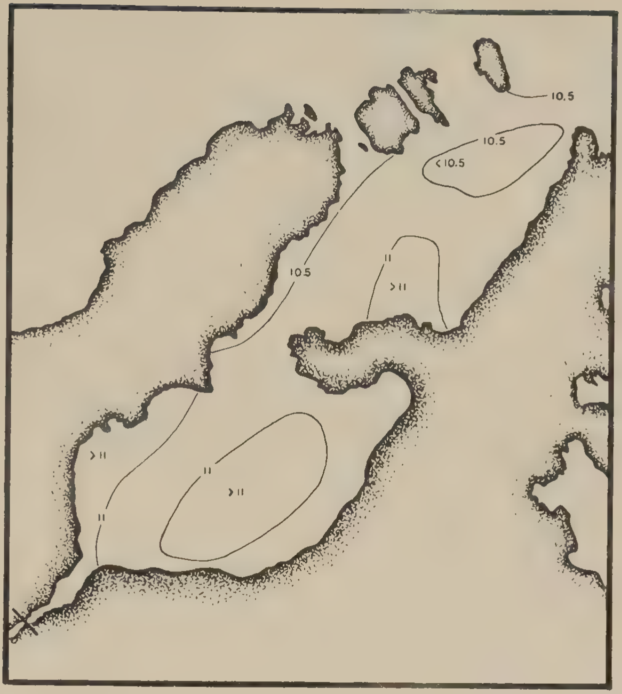


FIGURE 18.—Surface temperature, degrees C., slack before flood, cruise L–3, July 30 to August 4.

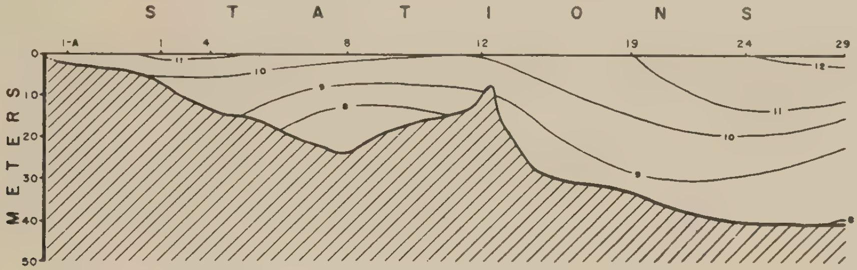


FIGURE 19.—Temperature, degrees C., along longitudinal axis of estuary at slack before ebb, cruise H–1, June 25 to July 2. (Data of station 8 missing.)

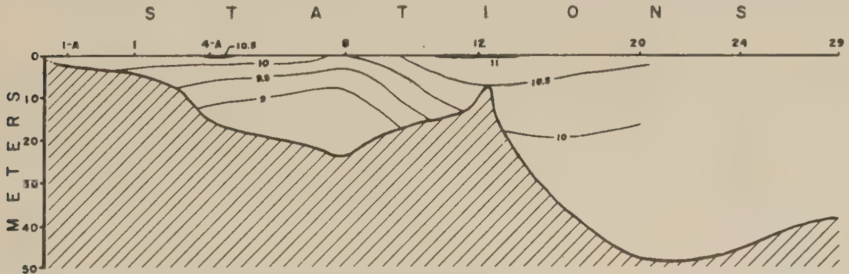


FIGURE 20.—Temperature, degrees C., along longitudinal axis of estuary at slack before ebb, cruise H–2, July 27–29.

ng cruises H–1, H–2, and H–3, (figs. 19, 20, 21) exhibited only slight gradients. Although ch greater depths existed in Outer Bay, bottom peratures remained within 1° C. of those in er Bay.

On cruises H–1 and H–3, all subsurface isotherms in Outer Bay sloped upward toward the sill at The Narrows. Since cruise H–2 was not completed, slopes of isotherms in Outer Bay for that cruise could not be determined.

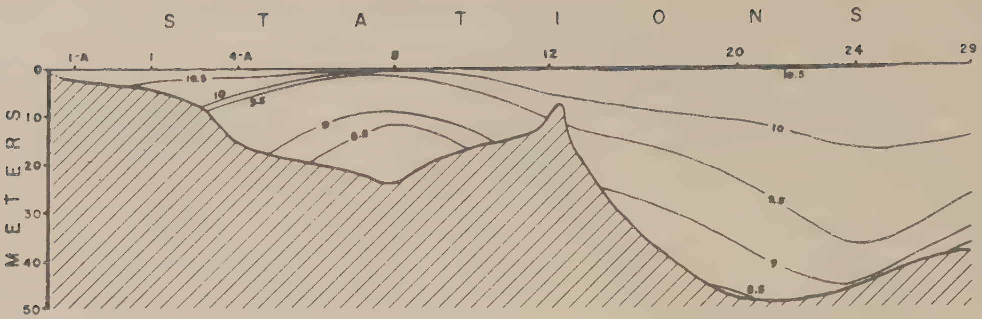


FIGURE 21.—Temperature, degrees C., along longitudinal axis of estuary at slack before ebb, cruise H–3, July 30 to August 4.

Vertical temperature distribution at slack before flood differed little from that at slack before ebb and is not discussed here.

Temporal Temperature Distribution

Figure 22 depicts the temporal variation of temperature for Inner Bay at reference station 2 between April 3 and August 21. It also includes daily maximum air temperature and daily observed maximum temperature of Sashin Creek. Conditions at reference station 2 during the first half of April were nearly isothermal, with some slight stratification appearing during the latter part of the month and persisting into June.

Until early June, surface waters were colder than those immediately below the surface. Highest temperatures (6° to 7° C.) began at a depth of about 2 meters. Comparatively rapid warming occurred in June and July. The highest temperature of the entire period of observation (12.2° C. at the surface) was recorded on July 11. This

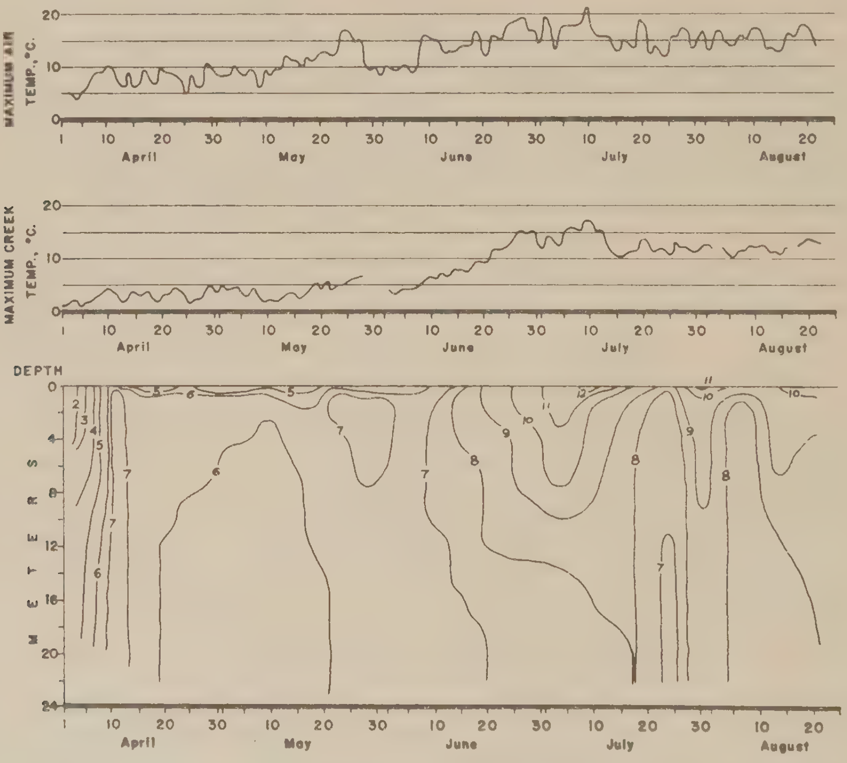


FIGURE 22.—Upper: Maximum daily air temperature, degrees C., Little Port Walter, April 1 to August 21, 1959. Center: Maximum observed daily temperature of Sashin Creek, degrees C., April 1 to August 21, 1959. Lower: Temporal sequence of water temperature, degrees centigrade, at reference station 2, April 3 to August 21, 1959.

rming trend coincided with a similar increase air temperature which culminated in a high of 1° C. on July 10. Fluctuating air tempera- es during the rest of the observation period e reflected in alternate warming and cooling of water, particularly evidenced by changes in ition of the 8° and 9° C. isotherms.

RANSPARENCY AND OXYGEN IN INNER BAY

'ransparency was measured weekly at reference ions 1, 2, and 3, and at all cruise and anchor tions between April 3 and August 31. Obser- ions of this parameter at reference station 2 presented temporally in figure 23.

'ertical distribution of oxygen was observed eference stations 2 and 3 on June 6, and weekly reference stations 2, 3, and 4 from July 11 to gust 21. Temporal distribution at station 2 resented in figures 23 and 24. Oxygen concen- ion was greater than 6 p.p.m. at all depths ll three stations except station 2 (located at the pest part of Inner Bay). There, oxygen at ths of 20 m. and greater (22 to 24.5 m., depend- on height of tide and exact point of sampling) usually less than 6 p.p.m. The week-to-week iations in oxygen at 20 m. at station 2 are wn in table 2 (oxygen at 15 m. is included for parison).

t 15 m. oxygen showed no tendency to become leted, fluctuating between 6.58 and 9.00 p.p.m. 20 m., however, changes of considerable magnitude occurred. Highest observed oxygen content at that depth was 9.50 p.p.m. on June 6. It decreased by 6.75 to a low of 2.75 p.p.m. on July 11, then increased sharply to 7.34 p.p.m. on July 17. A further slight increase of 0.32 p.p.m. during the following week resulted in a secondary high of 7.66 p.p.m. on July 24. Between July 24 and 31 it decreased by 2.38 p.p.m. to a value of 5.28, then rose gradually to 5.58 on August 14. A week later it again appeared to be decreasing rather rapidly, having fallen to 4.15 p.p.m. on August 21.

TABLE 2.—*Comparison of week-to-week variation in oxygen at 15 and 20 m., reference station 2*

Date	P.p.m. at 20 m.	P.p.m. at 15 m.
June 6	9.50	9.00
June 13, 20, July 4	(1)	(1)
July 11	2.75	7.68
July 17	7.34	6.81
July 24	7.66	7.87
July 31	5.28	7.18
August 7	5.45	6.78
August 14	5.58	7.22
August 21	4.15	6.58

[1] No observations.

Both transparency and 20-m. oxygen, as observed at reference station 2, exhibited temporal variations which correlated with the corresponding precipitation regime. In figure 23, the trend of the transparency curve correlates directly with the precipitation trends. Periods of increased precipitation corresponded with increased transparency, and periods of decreased precipitation

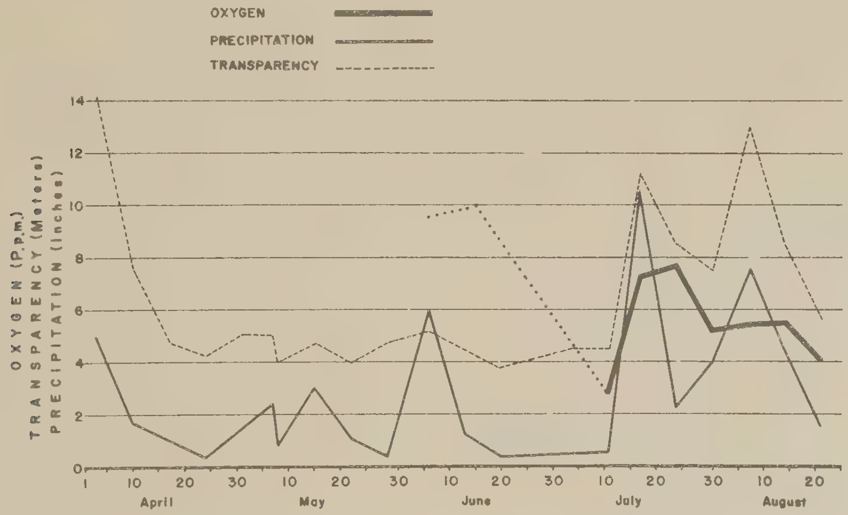


FIGURE 23.—Regimes of transparency and 20 m. oxygen at reference station 2, and precipitation as observed at Little Port Walter, April 3 to August 21, 1959. Each point on the precipitation curve represents the total for that day plus the 6 preceding days.

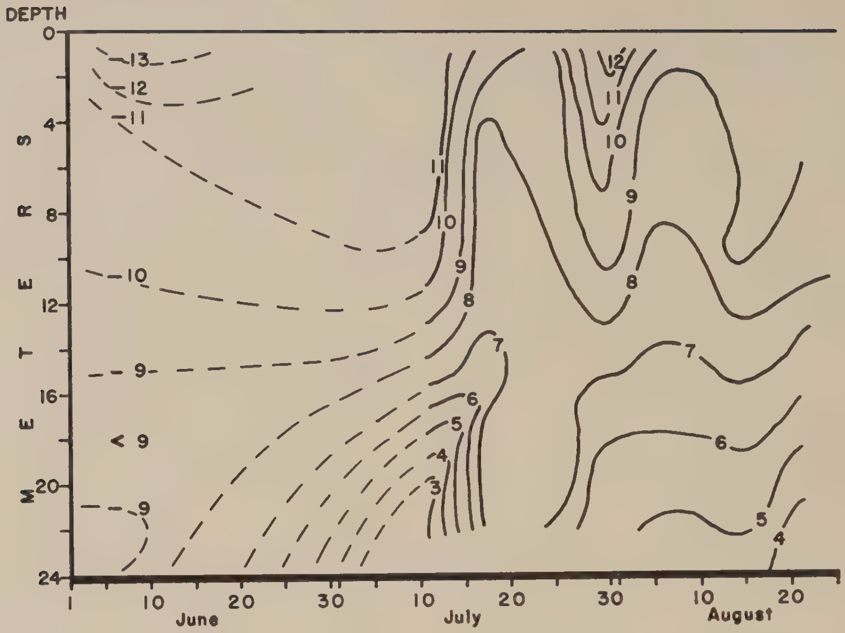


FIGURE 24.—Temporal sequence of dissolved oxygen, p.p.m., at reference station 2, June 6 and July 11 to August 21, 1959. Uppermost samples taken at depth of 1 meter.

with decreased transparency. Oxygen at 20 m. increased during two 1-week periods of heavy precipitation, continued to increase slowly during ensuing 1-week intervals of greatly reduced precipitation, and then decreased as precipitation remained low.

Between July 11 and 17, extremely heavy rainfall, 10.5 inches, coincided with large increases in transparency and 20-m. oxygen. From July 18 to 24, a period of very light precipitation, 2.4 inches, transparency decreased, while oxygen continued to increase slightly. During the week of July 25 to 31, precipitation measured a comparatively light 4.02 inches, and both transparency and oxygen decreased.

Relatively heavy precipitation (7.6 inches) between August 1 and 7 coincided with a large increase in transparency and a small increase in oxygen. Precipitation and transparency declined during the succeeding week (until August 14), while oxygen increased slightly. Precipitation was light during the last week in which observations were made, August 15–21, and both transparency and oxygen declined.

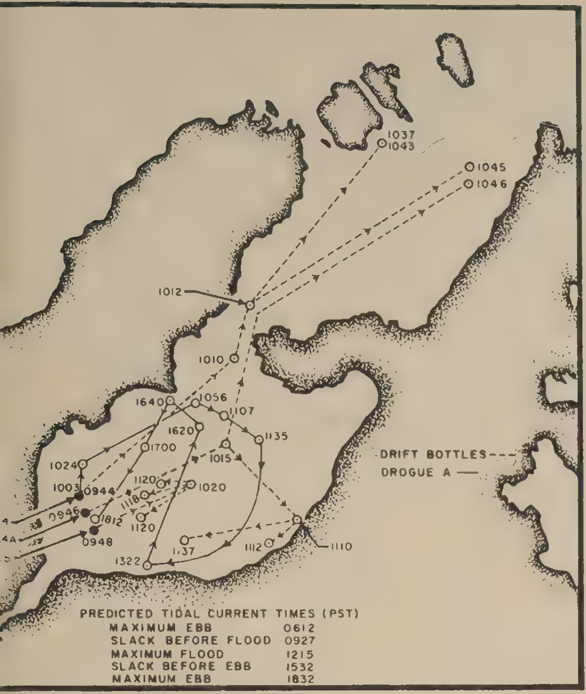
Two 3-week cycles were thus described: one between July 11 and 31, the other from August 1 to 21. Each was characterized by: (1) a week of heavy rainfall followed by 2 weeks of relatively light precipitation, (2) changes in transparency correlating directly with intensity of precipitation, and (3) 2 weeks of increasing oxygen values at 20 m. followed by a week of decrease. In each case, the increase in oxygen corresponded with the week of heavy precipitation.

On the basis of these two cycles, the probable trend of the oxygen curve between June 6 and July 4 is shown as a dotted line on figure 23.

DROGUES AND DRIFT BOTTLES

During the summer, drogues and drift bottles were released in Inner Bay at both high and low flows of Sashin Creek.

On August 5 the rate of flow of Sashin Creek rose sharply because of heavy rains. Estimated flows on the 4th, 5th, 6th and 7th were 0.096, 0.688, 0.728, and 0.329 million cubic meters per day respectively. The direction of flow in approximately the upper meter was observed on August 7, utilizing drift bottles and drogues. The drift bottles measured the movement of the top 0.25 m. of the water column; the drogues measured the 0.60-m. layer immediately below the 0.25-m. layer. Eight bottles and one drogue (*A*) were released at cruise station 4, seven bottles at station 4-A, and eight bottles at station 5. All releases were made about 1½ hours after the beginning of floodtide.


1037
1043
1045
1046
1012
1010
1640
1056
1107
1620
1135
1700
1015
1024
1003
0944
1120
1020
1118
0946
1812
1120
4
4A
0948
1137
1112
1110
1322
DRIFT BOTTLES
DROGUE A
PREDICTED TIDAL CURRENT TIMES (PST)
MAXIMUM EBB 0612
SLACK BEFORE FLOOD 0927
MAXIMUM FLOOD 1215
SLACK BEFORE EBB 1532
MAXIMUM EBB 1832

IGURE 25.—Paths of travel of drift bottles and drogue
August 7, 1959. Times of position fixes are indicated.
winds during entire period.

nd was calm during the entire period of obser-
ion. Paths of travel of the bottles and of
gue *A* are presented in figure 25.

ll bottles released at station 4, in the north
of the bay, moved nearly straight downbay
ard the tip of The Neck, curved into The
rows, and passed through Outer Bay to Chat-
Strait in about an hour. Drogue *A*, released
ultaneously with these bottles, did not enter
Narrows. Upon approaching the tip of The
k it swung to the right, followed a curved path
ard station 16 on the south shore, and con-
ued upbay to the vicinity of station 10. It then
ved away from shore toward The Narrows, and
he end of flood was about 150 m. southwest of
tip of The Neck. During the first 3 hours
ebb it moved toward the head of the estuary
ough the northern part of Inner Bay to a
tion near cruise station 4.

ll drift bottle observations were made during
dtide (fig. 25).

he seven bottles released at station 4-A moved
g the axis of the bay to between 90 and 140 m.
The Neck. Here two of them turned to the
and passed out through The Narrows, while the remaining five turned right and moved to station 16 near the south shore. From there they drifted slowly along shore in an upbay direction. These five bottles, from their initial point of release, followed a path similar to that of the drogue, rather than that of the bottles released at station 4.

All bottles from station 5 moved downbay, paralleling the paths of those from 4-A. After drifting about 230 m., they reversed direction and fanned out, moving very slowly back toward the head of the bay.

During periods of reduced fresh-water runoff the surface layer did not run out of the estuary on floodtides. Drogues were released in Inner Bay under conditions of low streamflow to ascertain whether the basic circulation pattern was otherwise similar to that observed during high streamflow.

On August 11, when the stream was discharging about 0.07 million cubic meters per day, single drogues were released during early flood at stations 8 (drogue *B*) and 9 (drogue *C*) and recovered several hours later before the end of flood (fig. 26). Drogue *B* pursued a circular, clockwise course, while drogue *C* moved diagonally upbay and acrossbay toward the north shore.

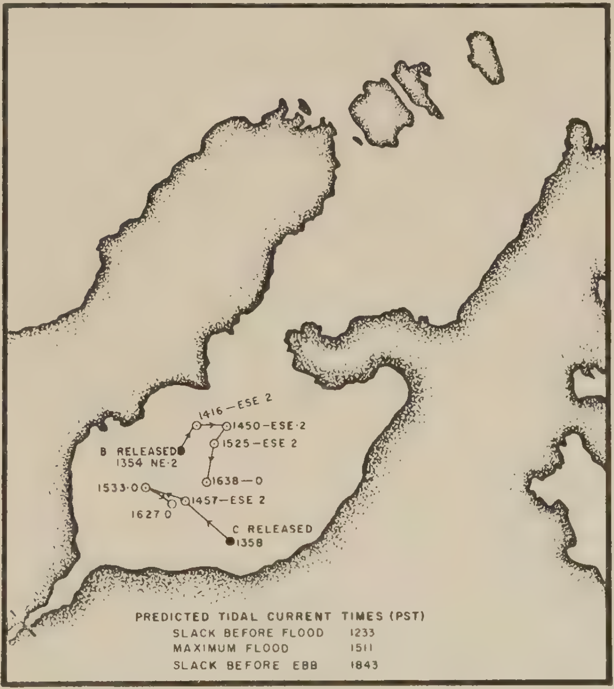

1416—ESE 2
1450—ESE·2
1525—ESE 2
B RELEASED
1354 NE·2
1638—0
1533·0
1457—ESE 2
1627 0
C RELEASED
1358
PREDICTED TIDAL CURRENT TIMES (PST)
SLACK BEFORE FLOOD 1233
MAXIMUM FLOOD 1511
SLACK BEFORE EBB 1843

FIGURE 26.—Paths of travel of drogues *B* and *C*, August 11, 1959. Time and wind indicated at each position fix.

On August 19, when stream discharge was 0.10 million cubic meter per day, single drogues were again released at stations 8 (drogue D) and 9 (drogue E). Set adrift during early flood, they were observed until late ebb (fig. 27). Drogue *D* followed a net clockwise path. During flood it moved toward the south shore, thence to the head of the bay near the mouth of the stream, from where it started downbay shortly before the beginning of ebb. During ebb it continued to move down through the northern part of the bay toward The Narrows. Drogue *E* followed a rather aimless spiral drift during its first several hours of travel, eventually moving very close to the south shore, along which it passed in a northeasterly direction to eventually ground shortly after the beginning of ebb. After being re-released near shore, it moved upbay along shore during the remainder of its drift. Drogues *D* and *E* were both recovered at the fifth hour of ebb.

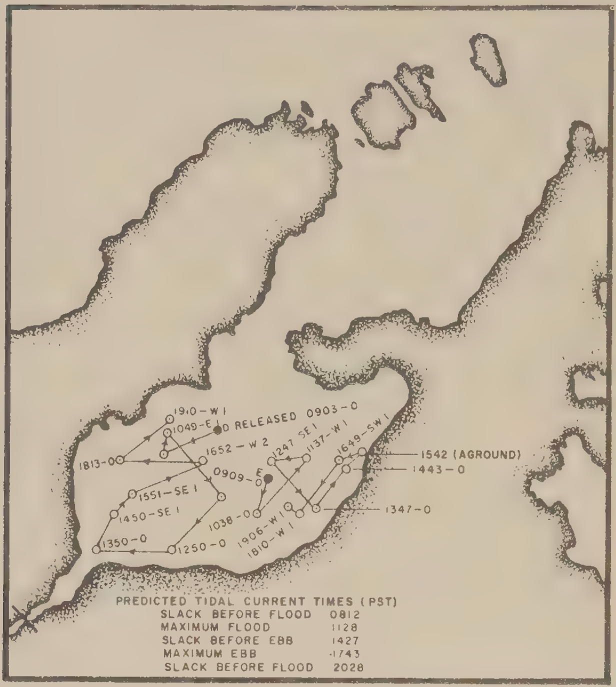


FIGURE 27.—Paths of travel of drogues *D* and *E*, August 19, 1959. Time and wind indicated at each position fix.

Medusae were in the estuary throughout the summer, usually in large numbers. They were never found in the upper freshened layer, appearing to come no closer to the surface than the top of the intermediate layer. Repeated visual observation indicated that these planktonic animals were effective neutrally buoyant drogues, and observations of their drift were helpful in discerning water movements. During times of greatly increased stream discharge, they were found in abnormally large concentrations at the extreme head of Inner Bay. Under such conditions the bottom in that region was covered with dead medusae. Their death was apparently caused by rupturing resulting from osmotic imbalance. A recent paper (Marshall and Hicks, 1962) substantiates my opinion that the medusae did not control their horizontal movements, but moved as freely floating bodies directed by the current.

DISCUSSION

CIRCULATION IN THE ESTUARY

Little Port Walter estuary exhibited normal oscillating tidal movements, which took the form of a standing wave. Slack waters coincided with high and low water, with maximum flows occurring approximately halfway between slacks. With the exception of the top 0.3 to 0.6 m. of water, which frequently ran out of Inner Bay throughout the tidal cycle, bidirectional currents were unusual, and movement of the entire water column through The Narrows was into Inner Bay during flood and out during ebb. Similar movements appeared to be the normal regime in the passages connecting Outer Bay with Port Walter Bay and Chatham Strait. For the most part, an equilibrium was apparently maintained by an excess of ebb transport over flood transport which was sufficient to carry off the fresh-water drainage. The discussion of basic circulation features which follows therefore refers to a net circulation achieved as a net product of the oscillating tidal movements.

Basic Features of Circulation

Inner Bay has the basin characteristics of a fiord. It is separated from Outer Bay by a sill at 5 m. and has a maximum depth of 21 m. The average depth is about 12 m., or approximately 2½ times the sill depth. (All depths are referred to datum.)

The fundamental net circulation of Inner Bay in the summer of 1959, as inferred from distribution of parameters and corroborated by direct observation, corresponded to that described for ords by Pritchard (1955) and Tully (1949). he fresh-water runoff was contained in a shallow p layer (figs. 10, 11, 12, and 13). This layer as a region of mixing between the fresh water nd the underlying sea water. Salinity increased apidly with depth in the upper few meters. The 0 °/oo isohaline was rarely found deeper than m. At greater depths the water was of nearly onstant salinity, varying only between 30 and 2 °/oo. This water possessed the salinity and emperature characteristics of the deep water of uter Bay (figs. 10, 11, 12, 19, 20, and 21). In gures 10 and 12, the 30 and 31 °/oo isohalines, hich rose from deep positions in Outer Bay to pproximately the 5-m. depth in Inner Bay, robably marked the lower limit of the interediate layer (Pritchard, 1955) in which the net ow is directed up the estuary. The upper rtion of this layer was probably delimited by ne 25 °/oo isohaline, which was never observed come to the surface in Inner Bay. Sea water ntrained in the intermediate layer extended to ne waterfall at the head of the estuary, where ottom salinities greater than 30 °/oo were rounely observed in 2 m. of water. Progressive award surfacing of isohalines less than 25 °/oo robably indicated that they were contained in ne upper layer in which net flow is seaward. ccording to Pritchard (1955), in this layer "the lt content increases in the seaward direction as result of advection and mixing of saltier water om below."

eep-Water Movement in Inner Bay

The deep water below the intermediate layer xhibited an irregular upbay movement. The recipitation-transparency-oxygen cycles of July 1–31 and August 1–21 suggested a sequence of eriods of alternating increase and decrease in ate of movement of this deep water. Although ne increases in transparency and in oxygen at 0 meters coincided with heavy precipitation, the ly appreciable lowering of salinity was confined a very shallow surface layer (fig. 13). It was nerefore evident that the increased oxygen connt of the deep water was not a result of downard mixing of the additional fresh water. The creased transparency likewise could not be cribed directly to the presence of the runoff ater, the turbidity of which was greater than at of the runoff during the immediately previous nditions of low flow.

The replenishment of oxygen and increase in transparency must therefore be attributed to a movement across the sill of deep water from Outer Bay. On July 17 oxygen content near the bottom of reference station 4 in Outer Bay was higher (9.88 p.p.m.) than at any other depth sampled in that station on that day. Since this observation coincided with the increase of oxygen at 20 m. in reference station 2, it further suggested an upbay movement of deep water which could have ridden over the sill and into Inner Bay.

The relationships between precipitation, transparency, and oxygen suggested that the movement of subsurface water across the sill from Outer Bay was in response to the mechanism of a salt pump. Hachey (1934) and others described such a mechanism in which the addition of fresh water resulted in a mixed layer of lowered salinity moving seaward (away from the mixing area) and a compensating current at a deeper level moving landward (toward the mixing area). Such differential movements are usually the net result of flows occurring over a complete tidal cycle. The rate of such a pumping is directly dependent upon the rate of fresh-water discharge into the estuary. In each of the observed precipitation-transparency-oxygen cycles, a regime of decreasing oxygen values at 20 m. was transformed to one of increasing values coincident with a change from light to heavy precipitation. After rainfall and runoff had decreased, oxygen continued to increase for another week before it declined. The intermediate layer and the deep water responded differentially to the pumping mechanism. Significantly increased rates of deep circulation were probably related to an effective frictional coupling of the deep layer to the intermediate during periods of high runoff resulting from periods of very heavy precipitation. Coupling of the two layers was likely insignificant when precipitation was light and runoff small. The movement of deep water at such times was sluggish or negligible, as shown by the observed tendency toward oxygen depletion. The lag period shown by oxygen may be due to replenishment during the momentum dieout of the deep layer.

Further evidence of increased subsurface flow toward the head of the bay during periods of heavy runoff was furnished by the abnormally large concentrations and deaths of medusae at the extreme head of the bay during times of greatly increased stream discharge. The medusae were apparently transported to the head of the bay within a counterflow that had increased its upbay rate of movement in response to the increased fresh-water discharge. Upwelling due to turbulent vertical mixing would tend to carry them into the freshened layers to which they were osmotically incompatible.

The action of a salt pump in Inner Bay was also indicated by the upbay ebbtide movements of drogue *A* on August 7 (fig. 25). The drogue was observed at a time when stream discharge had been quite heavy for several days. On the day the drogue was set, stream discharge was 0.33 million cubic meters per day, and the day before it was 0.73 million cubic meters per day, the greatest rate measured during the entire summer. It is difficult to explain the movement of the drogue, which was counter to the direction of the tide, on any basis other than that it was contained within a counterflow maintained by the salt pump. Water in the upper 0.3 m. was moving rapidly out of the bay at the time, and there was a complete absence of wind. Although the concept of the salt pump is generally based on net movement of water over a complete tidal cycle, it does not seem unlikely that, in a severely stratified situation such as occurred in Inner Bay, the rapid outward movement of the top layer of freshened water could have initiated and maintained an upbay movement of the more saline intermediate layer even during ebb. A somewhat analogous situation was found in Lake Ontario by Anderson and Rodgers (1959), where the flow of the warm water of the Niagara River into the lake induced a counterflow of colder bottom water from the lake toward shore.

Relation of Surface Circulation to Stream Discharge

It is evident from the foregoing discussion that the discharge rate of Sashin Creek markedly influenced the circulation of the estuary, particularly in Inner Bay. This was true not only with the vertically oriented water movements associated with the salt pump, but also with the horizontal pattern of surface circulation.

Floodtide, high stream discharge.—The paths of travel of the drift bottles and drogue *A* on August 7 (fig. 25) indicated vertical differences in circulation within the northern part of Inner Bay and horizontal differences between the northern and southern parts of the bay. From the northern third of Inner Bay, that part of the water column contained within the top 0.25 m. passed out through The Narrows, through Outer Bay, and into Chatham Strait, even though the tide was flooding. Water in the 0.6 m. layer directly below did not escape but passed into the southern part of Inner Bay. Surface water from the southern two-thirds of Inner Bay did not pass into The Narrows during flood tide, but appeared to enter an eddy.

The most striking aspect of this circulation was that it indicated at least part of the surface layer escaped throughout the tidal cycle. This continuous outflow appeared to result from the hydraulic pressure caused by increased stream discharge. Under all conditions of runoff the effluent of the stream tended to be diverted to the north side of Inner Bay by the shoal on the south side of the stream mouth. There was always an intense vertical salinity stratification, with most of the fresh water contained in a shallow surface layer. On August 7 this superficial freshened layer was subjected to sufficient head from the stream discharge to force its passage out of the northern portion of Inner Bay during both ebbtide and floodtide. That portion of the downbay surface flow which impinged upon The Neck was deflected into a clockwise eddy which occupied the southeastern quarter of the bay. Hence, only that surface water moving through approximately the northern one-third of the bay was able to escape through The Narrows. The motion of drogue A on August 7 indicated that during floodtide on that day, no water below a depth of 0.3 m. escaped from any part of Inner Bay, but that the deeper layers responded to the normal floodtide forces rather than to the force exerted by the fresh-water discharge.

The distribution of surface salinity during cruises H–1 and H–3 (when stream discharge was high and hence similar to conditions of August 7) confirmed the positioning of the fresh-water effluent in the north side of Inner Bay and the presence of the eddy in the southern portion.

A similar condition of continuous outflow of the surface layer throughout the tidal cycle was found during a current meter anchor station in The Narrows on June 22 when melt water influx had raised the volume of flow of Sashin Creek to about 0.34 million cubic meter per day. Observations of the vertical current profile showed that the flow in the upper 0.3 to 0.6 m. was out of Inner Bay during floodtide. Below this depth ovement of water was into the bay during flood. e wind was light and variable.

Floodtide, low stream discharge.—Drogues *B*, *C*, and *E* (figs. 26 and 27), when released under ditions of reduced stream discharge drifted in same clockwise eddy movement as they did ring conditions of high stream discharge. This ly seemed to be a dominant feature of Inner y under all conditions of runoff. On the day t drogue *E* was released the clockwise eddy had parently shifted, possibly moving to a more trally located upbay position and initiating by upling action a counterclockwise eddy in the theastern portion of the bay. The surface inity of cruise H–2 (when stream flow was only 8 million cubic meter per day and hence com-able to that of August 11 and 19 when drogues *C*, *D*, and *E* were observed) tentatively con-ned such a shift of the clockwise eddy. The g recurving tongue formed by the 16 ‰ haline in the inner central part of the bay was ggestive of eddy motion. Such an eddy might ount for the relatively high salinity found ar the north shore (<19 ‰ at station 3), ce its motion could transport to that position e water of high salinity observed protruding in ough The Narrows during the same cruise. counterclockwise eddy geared to the clockwise tion could in turn account for the low salinity ich lay in the southeast part of the bay. As fresh water left the stream it could readily ss along the north side of the clockwise eddy and bsequently be carried south and thence down-y toward The Neck by the contiguous counter-ckwise motion.

Ebbtide.—During ebbtide there was no evidence a reversal of currents leading to counterclock-se circulation under any conditions of fresh-ter runoff. Drogue *E* moved upbay along the th shore as though contained in the southern ge of the clockwise eddy. Drogue *D* moved wn through the northern part of the bay toward e Narrows in a clockwise pattern. The drift of ogue *A*, which appeared to be counter to the ection of ebb, has been discussed.

The distribution of surface salinity at slack fore flood (cruises L–1 and L–3) tended to con-m the ebbtide circulation pattern inferred from ovements of the drogues. During both cruises, linity tended to be lower in the northern part of ner Bay, with isohalines of greater values occupying the south shore between The Neck and the shoal at the head of the bay. Such a distribution suggested that an admixed stream effluent moved through the northern portion of the bay toward The Narrows, and a counterflow that contained lesser amounts of fresh water moved to the southern portion. The result was a clockwise motion.

Abnormal Circulation in Outer Bay

Anchor stations confirmed that the normal ebbtide pattern in Outer Bay was outflow through the three functional channels into Port Walter Bay and Chatham Strait. Occasionally, however, a reversal of flow through the Outer Island-Light Point channel took place during the first several hours of ebb. This reversal was, at least in part, caused by strong southerly currents in Chatham Strait and was not observed to occur with any degree of regularity.

The ebb current in Chatham Strait runs south. The mouth of the estuary faces partially into this current, making it possible for Chatham Strait water to flow into Outer Bay through the channel between Outer Island and Light Point. Such inflows were occasionally observed shortly after the beginning of ebb. On some ebbtides no unusual currents were observed near the mouth of the bay; on others, strong currents passed close to the mouth of the bay without actually entering; and on some the current penetrated well into the bay. This intruding current had the appearance of a typical rip current, with attendant surface ripples and swirls.

When the inflow from the strait did take place, it had the effect of damming that portion of the outflow from the estuary which normally ran between Outer Island and Light Point. Strong currents then flowed from Outer Bay into Port Walter Bay through the mainland-Inner Island and Middle Island-Outer Island channels. The escapement through these two channels was entrained in the ebbing current in Port Walter Bay and carried to the strait.

The phenomenon described was particularly evident on August 17. A line of floating kelp and other flotsam marked the advancing front of water from the strait, which penetrated through the Outer Island-Light Point channel into Outer Bay as far as a line between Middle Island and the southeast shore halfway between stations 21 and 26. This intruding water escaped into Port Walter

Bay through the Middle Island-Outer Island channel at velocities up to 80 cm./sec. (1.6 knots). The ebbing Outer Bay current passed into Port Walter Bay through the mainland-Inner Island channel at velocities of 50 to 60 cm./sec. (slightly over 1 knot). Only a weak ebb current was present at The Narrows at this time, indicating that the strong flow through the mainland-Inner Island channel was composed principally of water from Outer Bay.

The inflow from the strait began at the beginning of ebb. At the end of 1 hour, the kelp line that marked the intrusion had passed back out to the entrance of the bay, although strong currents were still running between the mainland and Inner Island and between Middle and Outer Islands. In 2 more hours the system had dissipated, and normal outflow from the estuary had become established.

On another occasion (July 8) a strong current from Chatham Strait, with surface velocities up to 50 cm./sec., was observed to approach the mouth of Outer Bay, but, although it passed just to seaward of Outer Island, it did not enter the bay and did not appear to obstruct normal outflow. This occurred during a period of spring tides, as did the events previously described when the large intrusion of water from the strait took place.

On June 22, also during spring tides, observations at anchor stations at the three channels in Outer Bay failed to reveal any operation of this system of currents.

FRESH-WATER FLUSHING OF INNER BAY

Although the feasibility of computing flushing rates for such incompletely mixed estuaries as Inner Bay has been questioned, such an operation seems logical if one carefully defines what is implied by the term "flushing." As computed here, the flushing of Inner Bay refers strictly to the flushing out of the contained fresh water, and the flushing time is the length of time required to rid the bay of an amount of fresh water equal to that of the accumulated fresh water contained within it on any given high tide (i.e., at slack before ebb). Even in this restricted sense, the flushing of an estuary has definite biological implications in that it has a direct effect upon any suspended materials or planktonic organisms which enter the bay via a stream.

The flushing time of Inner Bay was computed for each of the three cruises at slack before ebb (cruises H–1, H–2, and H–3) after the method of Ketchum, Redfield, and Ayers (1951). From contoured cross sections of salinity distribution, the cross-sectional areas of water of various salinities were determined by planimetry. The fraction of fresh water in each of these areas was calculated from the salinity, using as a reference the highest salinity observed in the entire estuary during the cruise. From the fresh-water fraction, the area of fresh water contained in the cross section was determined, and, using the known distance between sections, the volume of fresh water contained within the bay was calculated. This volume of accumulated fresh water, when divided by the average daily volume of flow of Sashin Creek during the cruise period, gave the flushing time in days. The results are:

Cruise	Fresh-water accumulation (cubic meters)	Streamflow (cubic meters/day)	Flushing time (days)
H–1	0.35×10^6	0.33×10^6	1.1
H–2	0.20×10^6	0.08×10^6	2.5
H–3	0.32×10^6	0.24×10^6	1.3

The computed flushing times correspond rather closely, varying only between 1.1 and 2.5 days. The correlation between magnitude of streamflow and flushing time, with flushing time decreasing as streamflow increases, is obvious. When flushing time is plotted against streamflow for the three cruises, the points fall nearly on a straight line. While more observations are desirable, the results are highly suggestive of a direct dependence of flushing time of Inner Bay upon volume of flow of Sashin Creek. The probability of such a relationship is enhanced by the observations and conclusions regarding surface circulation of Inner Bay, where it appeared that the pressure exerted by the flow of the stream was one of the chief determinants of the pattern of circulation of the upper layers.

WATER TRANSPORT THROUGH THE NARROWS

On August 12 and again on August 19, an anchor station was occupied in The Narrows to obtain data on water exchange between Inner and Outer Bays. The station, located in midchannel, appeared to sample adequately currents passing through The Narrows. The bottom in that nstricted passage shoaled rather rapidly toward th shores, and dense kelp beds, particularly on south side, restricted water movements urring outside the midchannel region.

According to Sverdrup, Johnson, and Fleming 946, p. 568), the velocity of midchannel current a cross section is about one-third higher than average velocity for the entire cross section. rrent velocities observed at the anchor station ve accordingly been lowered by one-third to ke them more nearly representative of the obable average velocity through the section. dependent estimates of total water transport ough the section, using tide range and surface a of Inner Bay in the relationship

$$V=A\times 2_{\eta 0}$$

verdrup et al., 1946, p. 568), indicated that this justment was realistic. In the above equation, is the volume of the tidal prism (hence the lume of water that must move through The rrows through one-half tidal cycle), A the face area of Inner Bay, and $2_{\eta 0}$ the average tide ge.

On August 12 the predicted mean tide range for rt Walter was 2.1 m. The current in the upper -half meter ran out during the entire cycle of od and ebb. The outflow during flood appeared be caused by south to southwest winds of force 2, rather than by the pressure of stream dis- rge which measured only 0.07×10^6 cubic ters per day. The greatest observed velocity s 15 cm./sec. Below a depth of one-half meter rrents were too weak to operate the current ter, which required a minimum current velocity 7.5 cm./sec. for activation. Directional orien- ion of the meter, which was usually visible to bottom, indicated that the water below one- f meter did move out of the bay during the ebb l in on the flood.

Since movement of inflowing water was not asurable, inflow was calculated from

$$S_oV_o=S_iV_i$$

ere S is the weighted average salinity over one e of tide (ebb or flood), V is volume of water, the subscripts "*o*" and "*i*" are out and in, pectively.

Under steady state conditions, a salt balance is maintained, that is, the estuary becomes neither fresher nor saltier. Assuming such conditions, the calculated inflow represents the volume of incoming water needed to replace the measured outflow in the upper one-half meter to the extent that net salt transport through the section is zero. Any outflow which may have taken place below one-half meter could not be taken into account in this computation, since it was not known. This necessary omission had the effect of systematically lowering the estimates of total transport throughout the complete tidal cycle.

TABLE 3.—*Observations at anchor stations in The Narrows, August 12 and 19*

Item	August 12	August 19
Total transport out through The Narrows, m³/tide	0.32×10^6	0.915×10^6
Total transport in through The Narrows, m³/tide	*0.26×10^6	0.89×10^6
Excess, out less in (net transport), m³/tide	0.06×10^6	0.025×10^6
Volume of flow, Sashin Creek, m.³/tide	0.035×10^6	0.07×10^6
Difference, net transport minus streamflow, m.³/tide	0.02×10^6	(−)0.04×10^6
Weighted average salinity, incoming water, °/₀₀	29.4	27.9
Weighted average salinity, outgoing water, °/₀₀	23.9	25.6
Salt transport, in through The Narrows, kg./tide	7.9×10^6	25.3×10^6
Salt transport, out through The Narrows, Kg./tide	7.9×10^6	23.9×10^6

*Calculated.

On August 19 greater total transports through The Narrows were observed than on August 12. Tide ranges on August 19 were also greater; the average range during the observed cycle was 3.6 m. During the first 3 hours of flood the entire water column moved into Inner Bay, despite the fact that observed streamflow was nearly twice that observed for August 12 (0.07×10^6 m³/tide vs. 0.035×10^6 on August 12). On the 19th, however, wind was absent during most of flood, with only occasional slight gusts from the northeast. By the fourth hour of flood the upper one-half meter was running out and continued to do so until the end of ebb. The remainder of the column flowed in until slack before ebb. Current velocities were appreciably greater than those observed on August 12, with peaks of 23.5 cm./sec. and 24.0 cm./sec. at maximum flood and maximum ebb, respectively. Current velocities were consistently of sufficient magnitude for direct observation by current meter.

The results of August 12 and 19 are shown in table 3.

As a check on the results for August 12, transport was estimated from $V=A\times 2_{\eta o}$. The average given by this method was 0.49×10^6 m.^{3}/tide, and is appreciably greater than, but of the same order of magnitude as, the measured-calculated average of 0.295×10^6. This difference probably resulted from the inability to measure that outflow which took place below a depth of one-half meter and not from the lowering of observed current velocities by one-third. This conclusion is substantiated by the excellent agreement between the two methods obtained on August 19, when current velocities were sufficiently strong for direct measurement at all depths.

The results for August 19 were checked in the same manner. Calculated average transport was 0.93×10^6m.^{3}/tide, in excellent agreement with the measured average of 0.90×10^6.

Under steady state conditions, the excess of outflow over inflow should equal the fresh-water contribution to Inner Bay. Such an ideal balance was not obtained from the observations of either August 12 or 19. However, on both dates the estimated volume of flow of Sashin Creek must, realistically, be accepted as an approximation only. In addition, total transport in through The Narrows on August 12 could not be measured directly, and it is believed that the total transport out was only partially measured. In consideration of these factors, as well as the realization that water transport measurements of this type give, at best, approximate figures, the discrepancies between estimated streamflow and the net transport out of Inner Bay are not disturbing. The degree of agreement that was obtained is probably about all that should be expected.

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ARLY LARVAL STAGES OF THE SEABOB, *XIPHOPENEUS KRØYERI* (HELLER)

William C. Renfro and Harry L. Cook, *Fishery Biologists*
Bureau of Commercial Fisheries

ABSTRACT

Five nauplial stages and the first protozoeal stage of e seabob (*Xiphopeneus kroyeri*) have been described m larvae reared in the laboratory. With each molt e larva increases in length and becomes more advanced in its morphology. Differences in body structures among specimens in the same instar were noted and discussed.

The ultimate goal of shrimp research is to under- and the factors affecting population numbers. is includes the dynamics of the young through e juvenile stages. To this end, studies of the undance, distribution, and biology of larval naeids are being pursued by the Bureau's Bio- gical Laboratory at Galveston. In the Gulf of exico adjacent to this laboratory at least 13 naeid species occur. Thus, any measurement of e seasonal and areal abundance of the young the commercially important shrimps requires e differentiation of the various species at all velopmental stages. This report gives the early ages of one of these penaeid species. Dobkin 961) has adequately summarized the existing erature on penaeid larvae.

Xiphopeneus krøyeri is found from South Caro- a to the middle Atlantic coast of Brazil. As is also known from Puerto Rico, it probably curs along the coasts of other Caribbean islands. ithin this range the species varies greatly in undance, having commercial importance only the mid-Gulf States and along the northeastern ast of South America. Although its life history s not been extensively studied, the seabob is a toral species found most often at depths less an 6 or 7 fathoms and rarely in protected bays side the barrier islands.

METHODS AND MATERIALS

All descriptions and figures are from specimens reared in the laboratory. Gravid females were caught at sea and returned to laboratory aquaria. After spawning, eggs were pipetted from the bottoms of the aquaria into beakers of sea water and the resulting larvae observed continuously. As development proceeded, specimens of each larval stage were measured, photographed, and preserved in buffered 5 percent formalin. Details of rearing trials are included in the appendix.

Microscope magnifications ranged from 10× to 200×. Measurements to the nearest 0.01 mm. were made with an ocular grid calibrated against a stage micrometer. We observed, as did Hudinaga (1942), some growth and development of body features occurring between molts. For this reason specimens in the same instar may exhibit differences in the size and shape of body structures. Figures were drawn with the aid of a camera-lucida and represent a conscious effort to illustrate the "typical" or most prevalent form of each stage.

In the ventral aspect many details of the nauplial appendages are obscured. In order to illustrate as clearly as possible all morphological features, dextral appendages have been drawn as though they had been rotated on their axes.

Note.—Approved for publication July 9, 1962.

DESCRIPTION OF THE EGG AND NOTES ON HATCHING

Twenty-six viable eggs had a mean diameter of 0.16 mm. with extremes from 0.15 to 0.17 mm. Although the egg is demersal, sinking readily in still sea water, it is easily buoyed up by slight agitation of the water. The nauplius, surrounded by the embryonic membrane, fills the egg. In later stages its appendages and a well-defined ocellus (nauplial eye) can be clearly seen through the thin, transparent shell (fig. 1). Prior to hatching, rapid, vibrating movements of the nauplius occur at more or less regular intervals.

The emerging nauplius first forces one appendage through the egg shell, then moves this appendage violently to enlarge the opening through which it finally escapes. Immediately after hatching, the nauplius is curled with its appendages drawn in posteriorly along the sides of the body. It soon assumes the normal shape as shown in figure 2.

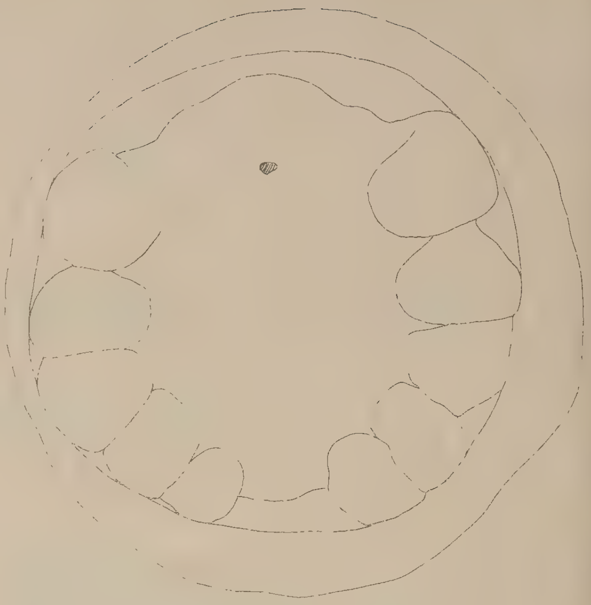


FIGURE 1.—Egg containing developing nauplius. Photomicrograph of ventral view.

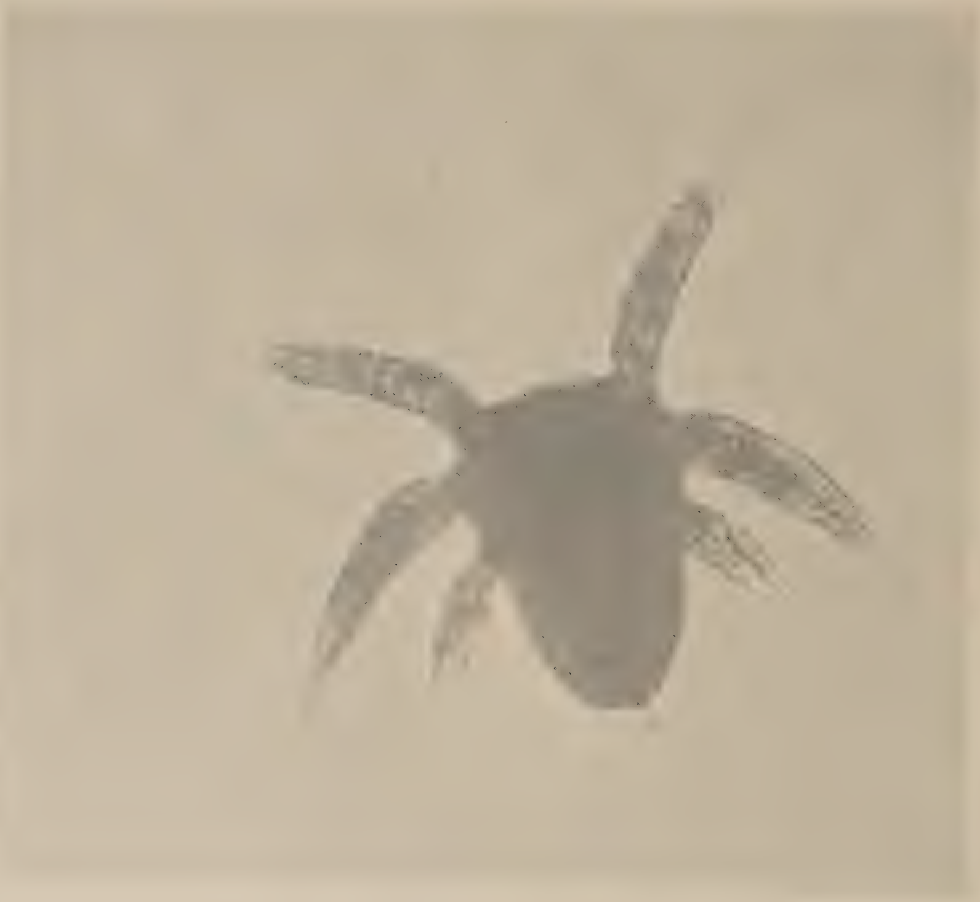


FIGURE 2.—Photomicrograph of Nauplius I, ventral view.

At rest, the nauplius lies dorsal surface down. s its appendages beat in unison, it rises a short stance then sinks when movement ceases. ctive swimming lasts approximately 2 seconds ith a rest period of about 8 seconds. Older auplii swim longer and rest less.

The yolk granules filling the body give it a ainy appearance. After preservation for several eeks in 5 percent formalin, all color is lost, and e yolk granules become opaque, giving the pre- rved nauplius a silver, grainy appearance in rong light.

DESCRIPTIONS OF STAGES

NAUPLIUS I

The Nauplius I of *X. krøyeri* has a short, pyri- rm body (figs. 3 and 4). Body length of 25 ecimens measured from the apical to caudal ds but excluding furcal spines averaged 0.26 m. Measurements across the dorsal surface the point of greatest width averaged 0.15 mm.

A small but distinct protuberance on the dorsal rface gives all nauplial stages a humpbacked pearance. The medial point of the hump falls between the origins of the second and third appendages. A slight depression is sometimes found posterior to the hump.

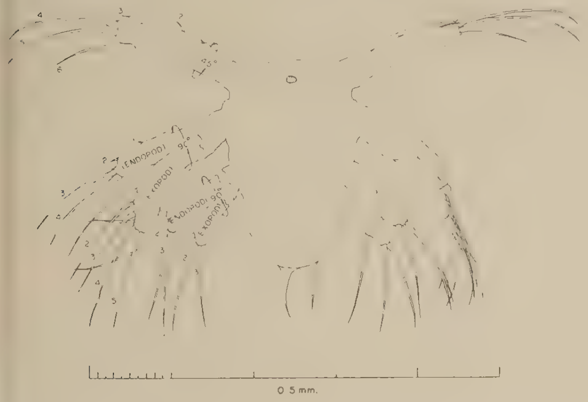


Figure 3.—Nauplius I, ventral view.

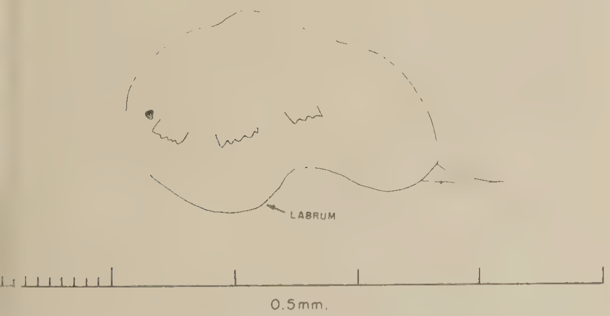


Figure 4.—Nauplius I, lateral view.

The ocellus lies in the longitudinal axis of the body near the anterior end and retains its position and color in all later nauplial stages. In living specimens it is reddish or rust colored but turns black in formalin.

The labrum or upper lip appears as a protrusion of the ventral surface. It is thickest at its posterior end and extends posteriorly to or just beyond the origins of the third appendages.

Two furcal spines arising at the posteroventral end of the body generally project directly backward but curve upward in some specimens. Viewed ventrally they are seen to curve inward.

Three pairs of appendages are inserted ventrally on the anterior half of the body. The anterior pair, or first antennae, are unbranched. The middle appendages, or second antennae, are branched into ventral endopods and dorsal exopods. The posterior appendages, or mandibles, are also branched into ventral endopods and dorsal exopods. All appendages bear setae which have been assigned arbitrary numbers to facilitate their description in the text. Starting with the anterior, proximal seta on each dextral appendage, the setae are numbered counterclockwise in the figure. It must be emphasized that setae are numbered on appendages which are represented as having been rotated around their axes. A given seta does not always retain the same number in subsequent figures. That is, with addition or loss of setae on an appendage, the setae are renumbered.

Each first antenna originates at the anteroventral edge of the body and curves outward. It possesses six setae. Setae 1, 2, and 3 are inserted on the anteroventral edge of the appendage. Seta 1 may not always be distinct; its position may merely be indicated by a slight protuberance. Setae 4 and 5 are terminal, and seta 6 arises from the posterodorsal surface near the end. On most specimens a short, spikelike spine, which may be the bud of another seta, projects from the ventral surface near the end of the first antenna.

The second antennae arise immediately posterior to the origins of the first antennae and are directed obliquely backward. The endopod of each second antenna appears as an extension of the basal portion and bears four setae. Setae 1 and 2 arise along the ventral midline, while setae 3 and 4 are terminal. A small, spikelike spine projects from the ventral surface at the distal end. The exopod of each second antenna is inserted on the dorsal surface. It is slightly longer than the endopod and bears five setae. Setae 1, 2, and 3 originate along the midline on the ventral surface, and setae 4 and 5 are terminal.

The posterior appendages, or mandibles, have their origins on the ventrolateral edges of the body about halfway between the anterior and posterior ends. Each endopod is directed posteriorly and bears three setae. Seta 1 is inserted on the posteroventral surface near the distal end, and setae 2 and 3 are terminal. The exopod branches from the dorsal surface of each mandible and bears three setae of nearly equal length. Setae 2 and 3 are terminal, and seta 1 is subterminal. Setation of the endopods and exopods of the mandibles remains constant in all subsequent nauplial stages.

NAUPLIUS II

Twenty-five Nauplius II specimens averaged 0.27 mm. in length and 0.15 mm. in greatest width (figs. 5 and 6). The labrum has a pronounced fold posteriorly, and a second fold, the labium or lower lip, can be seen behind the labrum in the lateral view. The two furcal spines are longer, straighter, and inserted farther apart than those of Nauplius I.

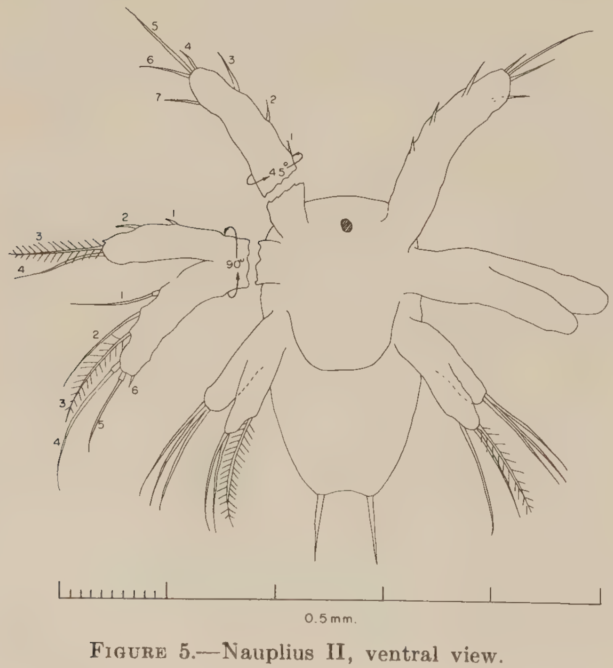


Figure 5.—Nauplius II, ventral view.

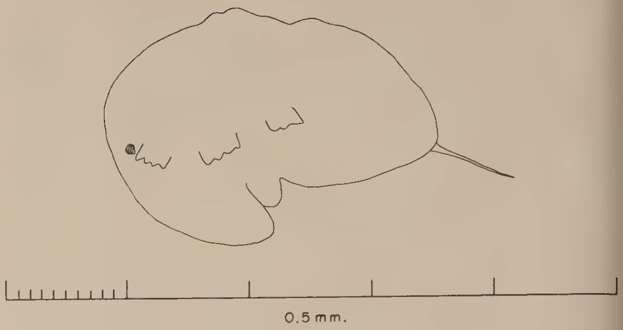


Figure 6.—Nauplius II, lateral view.

Shapes of the appendages are not changed, but all are slightly longer. Some setae, generally the longer ones, become plumose with the addition of setules along their lengths; however, this condition varies among specimens in this stage.

The spikelike spine on each first antenna of Nauplius I has lengthened to become seta 4, while the terminal and dorsolateral setae are shorter.

The endopod of each second antenna retains the setation of Nauplius I except that the two terminal setae are shorter. Each exopod of the second antennae gains a short sixth seta terminally. Setae 4 and 5 have short, cylindrical shanks at their bases. These basal shanks are also found occasionally on other long setae of second nauplii. Setae 1, 2, 3, 4, and 5 are generally plumose.

As previously stated, setation of the mandibles remains constant in all nauplial stages.

NAUPLIUS III

Nine Nauplius III specimens averaged 0.29 mm. in length and 0.15 mm. in width (figs. 7 and 8). Both the labrum and labium are larger. Four pairs of ventral appendages, which will appear externally in the next stage, can be seen beneath the cuticle in lateral view.

Three pairs of small furcal spines have been added, two pairs laterally (spines 1 and 2) and one pair medially (spine 4). The furcal spine count thus becomes 4+4. The posterior half of the body appears slightly more slender, and the caudal end shows definite bifurcation.

All longer setae are plumose in this stage, and the basal shanks, which first appeared in the preceding stage, are longer and occur more frequently.

Setation of the first antennae is unchanged.

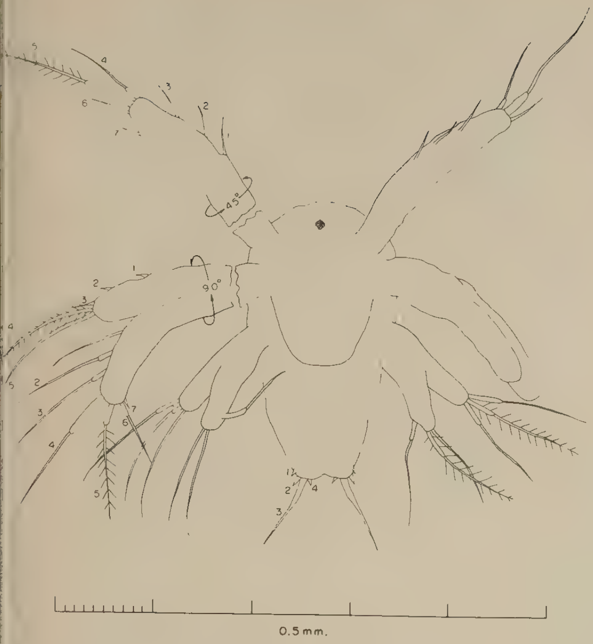


FIGURE 7.—Nauplius III, ventral view.

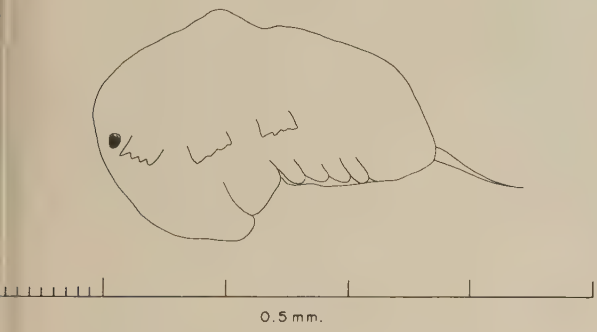


FIGURE 8.—Nauplius III, lateral view.

etae 1, 2, 3, and 4 are longer, and seta 7 is shorter an in the last stage.

On the endopod of each second antenna the ikelike spine, which was present in the preceding vo stages, has lengthened to become seta 3. The opod of each second antenna gains a small seta eta 7) terminally, and seta 6 has become longer. The bases of the mandibles in some specimens pear to be swollen.

NAUPLIUS IV

Measurements of 13 Nauplius IV specimens owed their average length to be 0.34 mm. and erage width 0.16 mm. The body is more elon-te and slender posteriorly (figs. 9 and 10). aint outlines of a carapace have appeared on the dorsal surface. A pair of "frontal organs" appear as slight protuberances at the anterior margin of the body. The labrum narrows posteriorly, and the labium can now be seen in the ventral view.

Four pairs of biramous appendages (the first and second maxillae and the first and second maxillipeds) are now prominent on the ventral surface of the posterior half of the body.

Definite, lobelike furcal processes are now apparent, and with the addition of one pair of lateral spines and another pair medially, the furcal spine count is 6+6.

Setation of the first antennae does not change. On the endopods of the second antennae, setation is unchanged except for the addition of a terminal spikelike spine inserted ventrally. The exopod of each second antenna acquires an additional seta, making its total setae count eight.

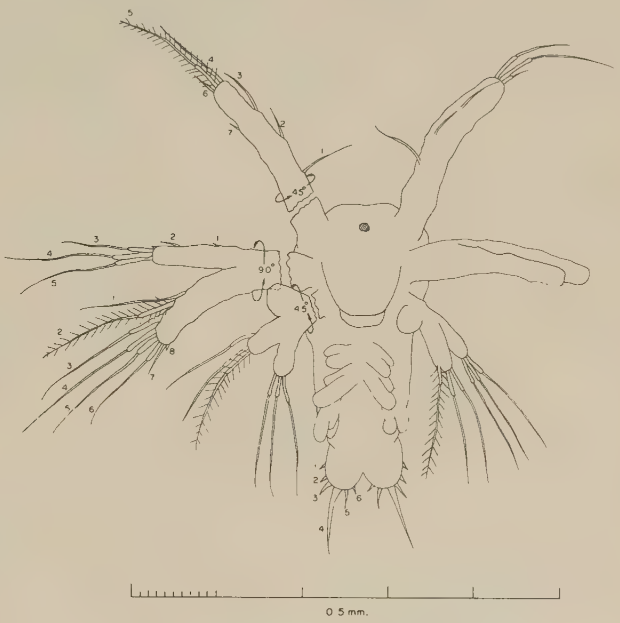


FIGURE 9.—Nauplius IV, ventral view.

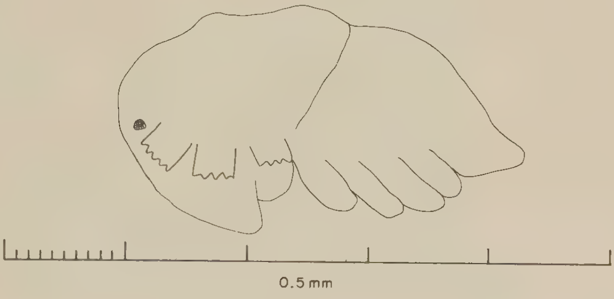


FIGURE 10.—Nauplius IV, lateral view.

Setation of the mandibles remains unchanged, but a prominent rounded lobe appears at the base of each. This is the rudiment of a masticatory organ, and combined with the appearance of the maxillae and maxillipeds, is the most characteristic feature of Nauplius IV.

NAUPLIUS V

Seven specimens of Nauplius V averaged 0.39 mm. in length and 0.16 mm. in greatest width. The body is more elongate, the carapace more prominent, and the frontal organs more sharply defined than in the preceding stage (figs. 11 and 12). The labrum is further narrowed posteriorly and the labium is now bilobed.

The maxillae and maxillipeds have lengthened and now bear two or three terminal setae on each branch.

The caudal furcae are further separated by a sulcus which has developed between them. With the addition of a pair of spines inserted medially, furcal spine count is 7+7.

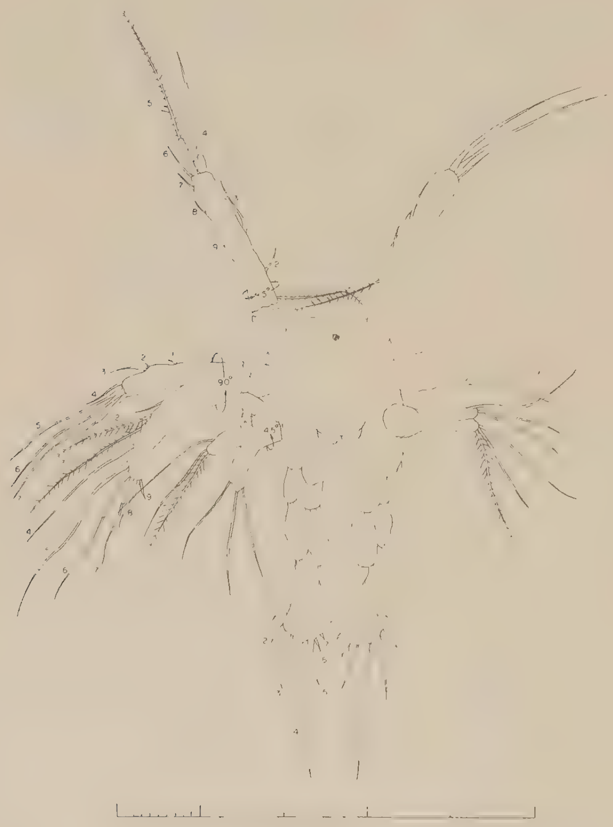


FIGURE 11.—Nauplius V, ventral view.

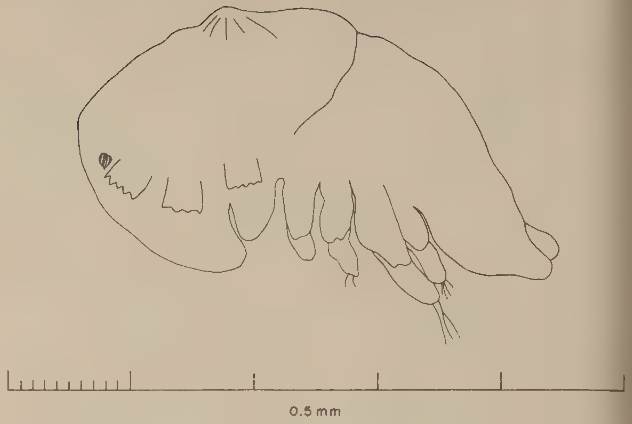


FIGURE 12.—Nauplius V, lateral view.

On each first antenna there are now three dorsolateral setae as a result of the addition of setae 7 and 9.

On the endopod of each second antenna a small seta (seta 2) is present near the base of seta 3, and the small, terminal bud which was present in the last stage has lengthened to form seta 4. Each exopod gains an additional seta to make its total nine.

As in previous stages, setation of the mandibles is unchanged, but the endopods are frequently transparent. The rudimentary masticatory organ at the base of each mandible is further enlarged and is shaped somewhat like a strawberry. Transparent, toothed structures are faintly discernible on its posterior surface.

PROTOZOEA I

Measured from the anterior margin of the carapace to the ends of the furcae, eight Protozoea I specimens averaged 0.69 mm. Six averaged 0.32 mm. in greatest carapace width and 0.36 mm. in carapace length (figs. 13, 14, and 15).

Although the Protozoea I does not move as rapidly as the Nauplius V, it is much stronger, swimming almost continuously with its ventral surface up. All appendages except the mandibles appear to aid in locomotion, and occasionally protozoea were observed to bend the abdomen beneath the cephalothorax and flip themselves when meeting an obstacle.

The carapace, which is somewhat flattened, fits loosely on the dorsal surface. The dorsal protuberance present in the nauplii persists but is not so prominent in this stage. The anterior edge of the carapace is divided into two lobes each of which

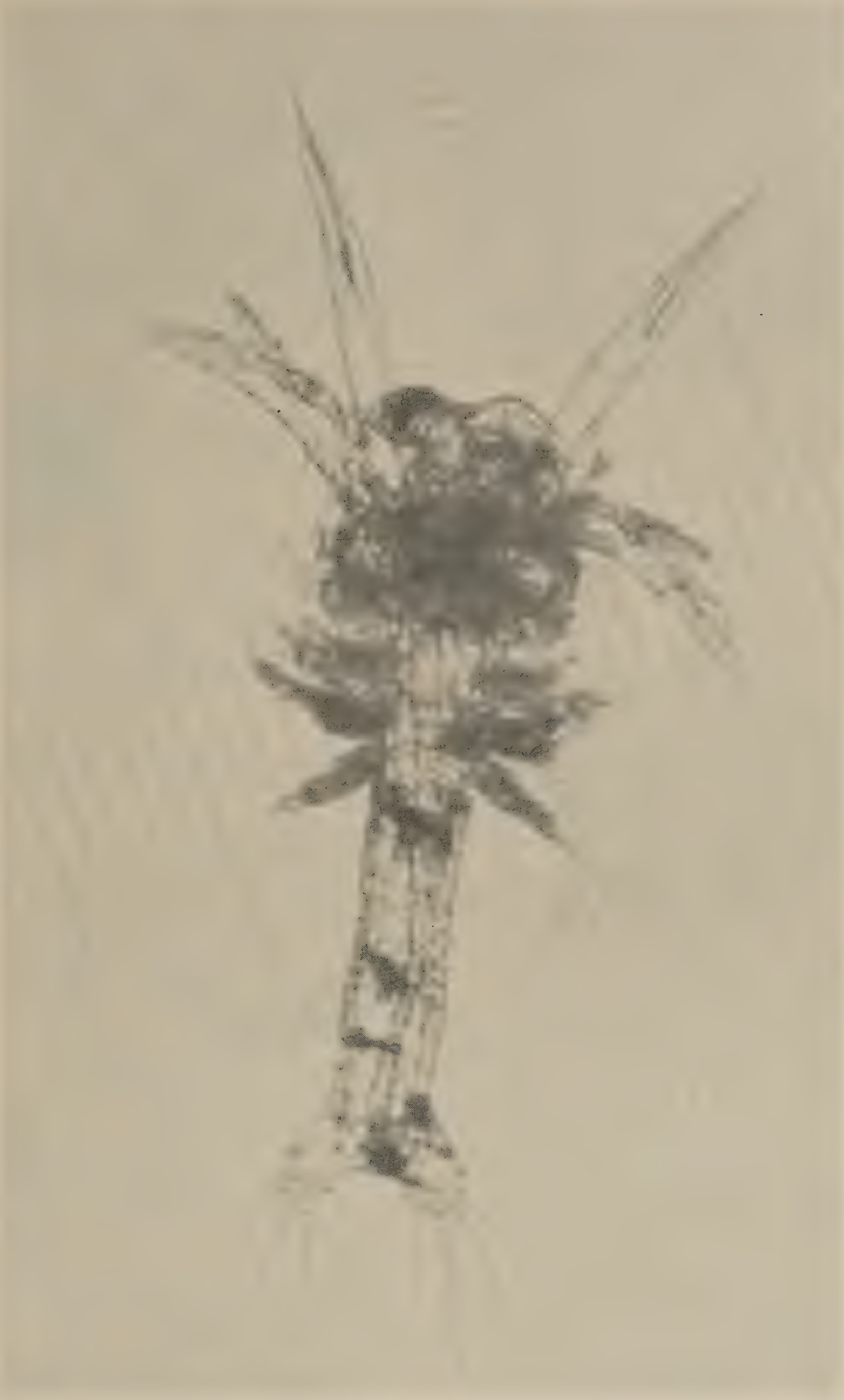


FIGURE 13.—Photomicrograph of Protozoea I, ventral view.

bears a well-developed frontal organ ventrally. The compound eyes as well as the ocellus can be seen beneath the carapace.

Behind the carapace the body is slender and segmented. The caudal end is divided into two lobes, each bearing seven furcal spines. These furcae are separated by a semicircular notch through which the anus opens. In the posterior portion of the body the intestine can be seen, flanked by long muscle fibers.

The labrum now has a stout, anterior spine, bears fine setae on its posterior margin, and partially obscures the mandibles. The masticatory processes of the mandibles are longer and curve inward, terminating in a ring of teeth (fig. 16). The larger teeth are prominent structures posterior to the labrum. Within each mandible a second ring of teeth is present. A small lobe directed laterally arises from the ventral surface of each mandible. The two lobes of the labium lie posterior to the mandibles and bear fine setae on their medial surfaces.

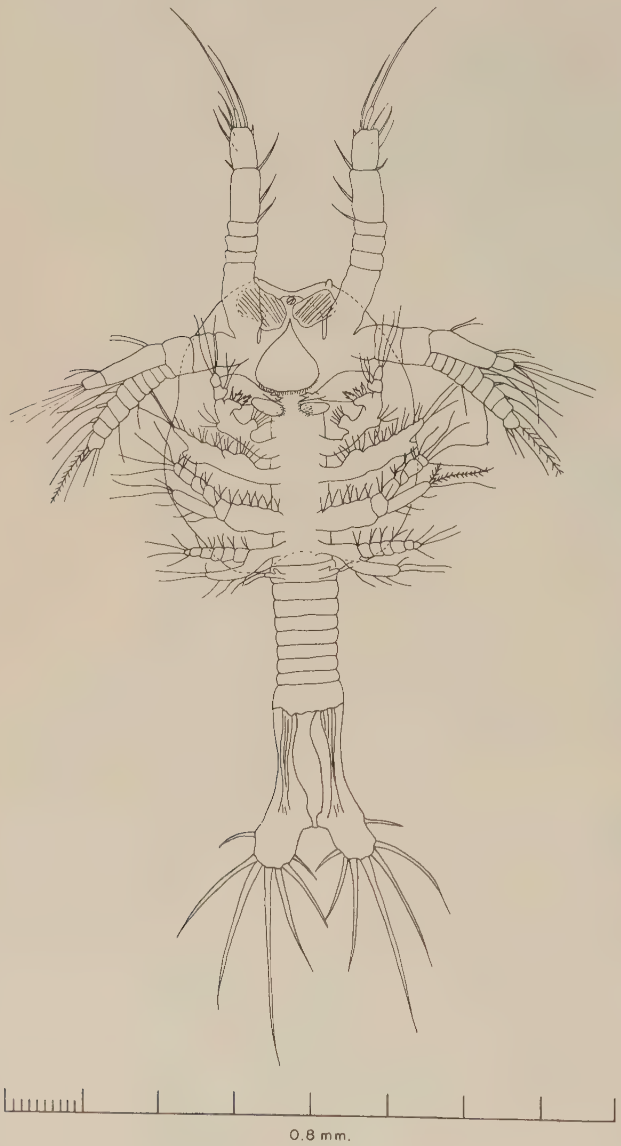


Figure 14.—Protozoea I, ventral view.

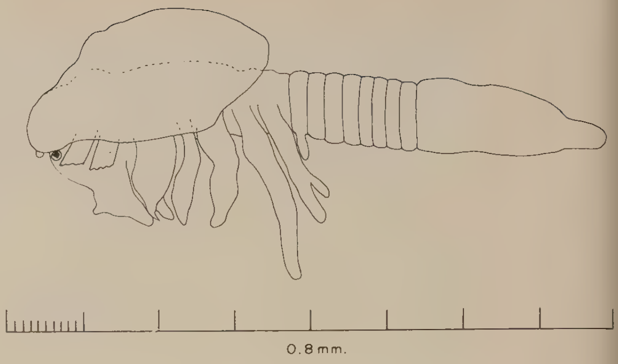


Figure 15.—Protozoea I, lateral view.

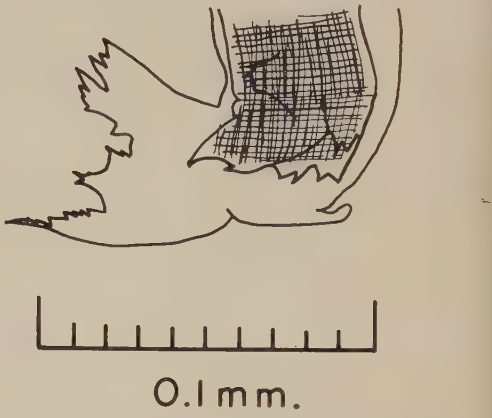


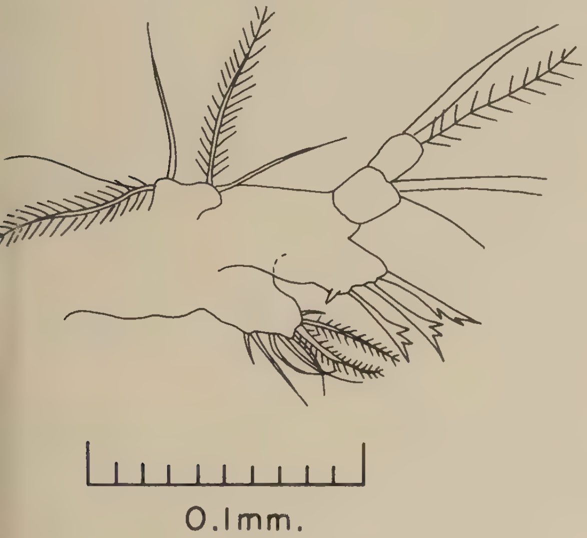
Figure 16.—Protozoea I, right mandible, posterior view.

Segmentation of all appendages occurs for the first time in this stage, although segments are indistinct in many cases. Each first antenna is divided into six or seven segments. Except for the appearance of a small bud terminally, setation of each first antenna is unchanged from that of the last stage.

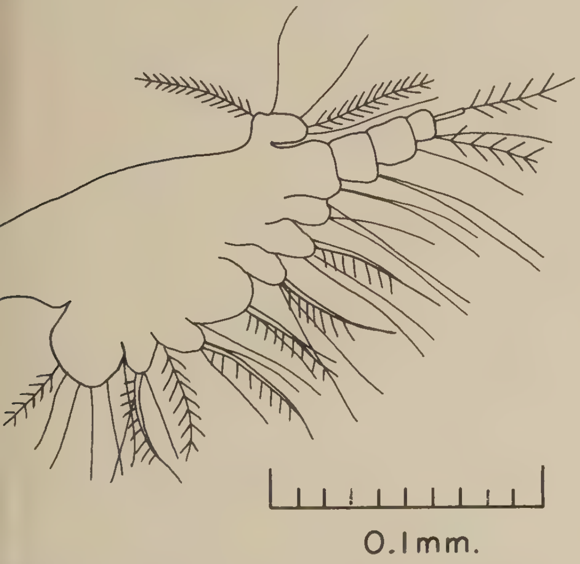
On each of the second antennae the basal portion, or protopod, is divided into 3 segments, the endopod into 2 segments, and the exopod into 9 or 10 segments. The first segment of the endopod bears two pairs of setae on its anteroventral margin: one pair proximally and the second distally.

ne distal segment bears five terminal setae. The opod of each second antenna bears five setae its anteroventral margin, one each arising from e fifth, sixth, seventh, eighth, and ninth seg-ents. Its 10th segment bears four terminal tae. The fifth and seventh segments also have single seta on their posterodorsal surface.

The protopod of each first maxilla (fig. 17) is segmented but has two lobes on its anterior argin. The proximal lobe bears eight short, ick setae, and the distal lobe bears three stout tae, which are barbed terminally. The endopod is composed of two segments bearing three setae each. The exopods of the first maxillae are present as small, spherical knobs, each of which bears four setae.



URE 17.—Protozoea I, right first maxilla, posterior view.



URE 18.—Protozoea I, right second maxilla, posterior view.

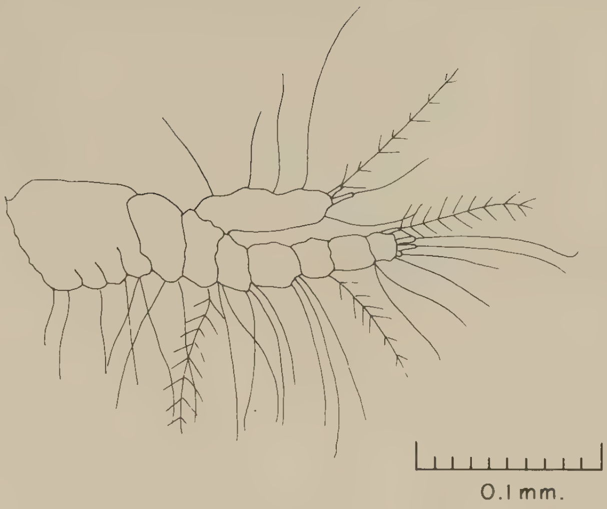


FIGURE 19.—Protozoea I, right first maxilliped, posterior view.

The protopod of each second maxilla (fig. 18) shows no segmentation but has seven small lobes on its anterior margin. The first four lobes are sometimes coalesced to form one large lobe. The first or proximal lobe bears six setae while the remainder bear three or four. Two setae also arise from the distal end of the protopod. The endopod is composed of three segments: the proximal bearing two setae; the middle, one; and the distal, three. The exopod is a small knob which bears five setae.

The protopod of each first maxilliped (fig. 19) is composed of three segments. The proximal segment has four lobes on its anterior margin, each bearing one or two setae. The second and third segments of the protopod also bear one or two setae. Each endopod has five segments, the first four bear one to three setae on their anterior margins and the fifth possesses five terminal setae. The exopod of each first maxilliped is unsegmented and bears four lateral and three terminal setae.

The second maxillipeds (fig. 20) closely resemble the first maxillipeds. Their protopods consist of four segments, each of which bears one or two setae. Each endopod is composed of six segments with the first five segments bearing one or two setae on their anterior margins and the sixth bearing three terminal setae. The exopod of each

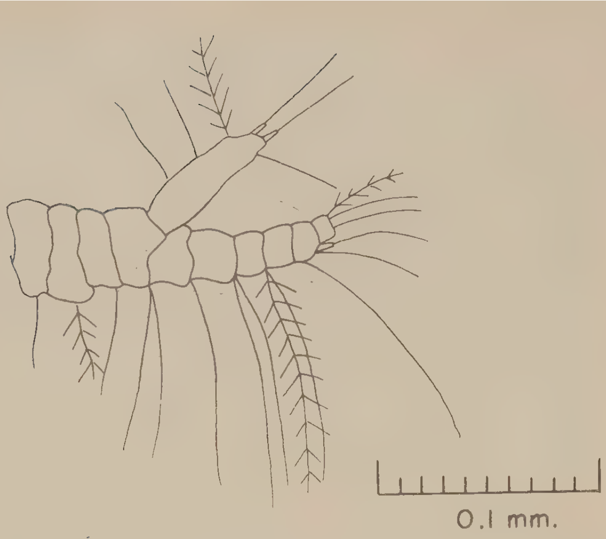


FIGURE 20.—Protozoea I, right second maxilliped posterior view.

second maxilliped is unsegmented and bears three posterolateral and three terminal setae.

Posterior to the second maxillipeds is a pair of small third maxillipeds. The exopods are considerably longer than the endopods and bear two terminal setae.

MORPHOLOGICAL VARIATION AMONG SPECIMENS WITHIN AN INSTAR

The development of these normally planktonic larvae was probably slower in the laboratory than in nature. For example, molting in some specimens continued for 15 minutes or more in the laboratory. In the sea, this process might be completed in much less time. It is possible, therefore, that the morphological variations discussed here were observable only because normal developmental rates were retarded.

Hudinaga (1942, p. 331) stated: "It may be said that in Crustacea the body-length increases only by moulting, but in some species there is a slight difference in the length immediately after one moult and before the next, an outstanding example of which is the zoea stage of *P. japonicus.*" During our rearing trials individual nauplii were isolated in small containers and observed periodically. Slight elongation of some body parts was observed, but actual, periodic measurements of the moving larvae were not attempted. The spines and setae of all preserved specimens were measured to the nearest 0.01 mm. These measurements were examined to determine the extent of variation in morphology among specimens in the same instar. The results showed: (1) Nauplius I. Fourteen specimens had one pair of furcal spines 0.04 to 0.05 mm. long and 10 specimens possessed one pair of furcal spines measuring 0.06 mm. The 10 specimens with larger furcal spines also had longer setae on all appendages. (2) Nauplius II. Ten specimens with furcal spines 0.06 to 0.08 mm. long had, in almost every case, longer setae than did 13 specimens with furcal spines 0.04 to 0.05 mm. in length. (3) Nauplius III. Three groups of specimens were distinguished (table 1); three with four pairs of furcal spines, four with three pairs, and two with two pairs. Specimens with fewer and shorter furcal spines also had shorter setae. Of interest was the fact that the furcal spines missing in the two groups having shorter setae were those spines which are added at this instar. (4) Nauplius IV. Four specimens with four pairs of furcal spines had, in most instances, shorter setae than the remaining five specimens with six pairs. (5) Nauplius V. Of seven specimens one had four pairs of furcal spines, one had five pairs, and five specimens had seven pairs. In general the specimens with fewer furcal spines had shorter setae.

Obviously, individual nauplii in the same instar differ considerably in their body dimensions. Several possible causes for these observed differences might be considered: (a) The nauplii with shorter and fewer furcal spines and setae may be malformed specimens which die before reaching the next instar. (b) The differences are the result of individual variation, some nauplii simply being smaller and less well developed than others. (c) These tiny larvae, covered with a thin cuticle, continue to develop and lengthen, during the period between molts.

Another cause for variation observed among individuals in the same stage of development lies in the molting process. Loss of the exoskeleton was observed to begin at the posterior end of the nauplius. The furcal spines and the posterior cuticle were shed first followed by the setae and exoskeleton of the mandibles, the second antennae, and the first antennae. In most cases, the body exoskeleton was lost in pieces. The molting of right and left appendages did not always occur simultaneously. Because molting of all parts was not instantaneous, a number of our specimens had only partially shed their exoskeletons. In one Nauplius IV specimen, for example, the right

E 1.—*Nauplius III, mean length of furcal spines and*
e in specimens with different furcal spine counts

[0.01-mm. units]

Process	Furcal spine count		
	2+2	3+3	4+4
spine 1	(1)	(1)	>1.0
spine 2	(1)	1.0	2.0
spine 3	6.0	7.0	10.7
spine 4	>1.0	>1.0	1.0
ntenna:			
a 1	2.0	2.3	8.0
a 2	2.0	2.5	3.3
a 3	5.0	2.8	5.7
a 4	5.0	6.0	12.3
a 5	9.0	11.8	17.7
a 6	5.0	3.8	4.0
a 7	(2)	>1.5	>2.5
antenna:			
dopod:			
Seta 1	>1.0	>1.0	>1.0
Seta 2	>1.0	1.5	>1.3
Seta 3	(2)	2.5	6.3
Seta 4	10.0	13.0	18.7
Seta 5	10.0	13.0	18.7
opod:			
Seta 1	5.0	7.0	12.0
Seta 2	5.0	11.8	17.3
Seta 3	6.0	12.5	17.3
Seta 4	10.0	13.0	22.0
Seta 5	6.0	10.8	15.7
Seta 6	3.0	5.8	9.7
Seta 7	>1.0	>2.0	1.3
bles:			
dopod:			
Seta 1	8.0	9.2	14.0
Setae 2 and 3	11.0	11.0	15.0
opod:			
Setae 1, 2, and 3	11.0	11.8	15.7

measured.
sent.

nd antenna had molted, while the left second
nna retained the exoskeleton of the previous
r, thus the right had more setae than the left.
sionally the exoskeleton of an appendage had
ned but was not completely shed at the time
reservation. Its new setae, which were visible
ath the old cast, were very small.

sted below are variations from the described
s:

NAUPLIUS I

e slight depression posterior to the dorsal
p was not present on a few of the specimens
ed.

e labrum varied in size from slight to very
inent.

ta 1 on the anteroventral margin of each first
nna was absent in 2 of 25 specimens.

ta 1 on the endopods of the second antennae
not present in 3 of 25 specimens.

NAUPLIUS II

me specimens, preserved in the process of
ing, exhibited appendage setation characteris-
f Nauplius II while retaining the Nauplius I
ion on the corresponding appendage of the
site side. Frequently, the cast of an append-age had only partially slipped off and obscured the new setae beneath it.

Addition of setules to the setae varied in individual specimens and among the different specimens. That is, some specimens had plumose setae on one appendage while corresponding setae on the opposite appendage or on another specimen lacked setules.

The shanks present at the bases of setae 4 and 5 on the exopods of the second antennae were also found randomly on all longer setae.

The terminus of seta 4 on the exopod of each second antenna was split in occasional specimens of Nauplius II and later stages. This seta is always the longest seta on the exopod although its number may change.

NAUPLIUS III

In three specimens a small median spine between the furcae was noted.

On two specimens having three pairs of furcal spines, seta 7 on the exopods of the second antennae was absent. Variation in the number of furcal spines has previously been discussed.

NAUPLIUS IV

Four individuals possessed four pairs of furcal spines, five had six pairs, and one specimen was too badly damaged to determine the spine count.

Seta 8 on the exopods of the second antennae was absent in two of six specimens which were otherwise in good condition.

NAUPLIUS V

Seta 2 on the endopods of the second antennae was missing in three of seven specimens.

PROTOZOEA I

No significant morphological differences were noted among the eight specimens examined.

SUMMARY

There are five nauplial stages during the early larval development of the seabob. With each molt the larva increases in length and becomes more advanced in its morphology. Differences in various body structures among specimens in the same instar are discussed. A characteristic which is usually sufficient to separate nauplial stages is the addition of one seta on the exopods of the second antennae with each molt. This and other characteristics are summarized in table 2.

TABLE 2.—*Counts of furcal spines and setae*

Stage	Furcal spines	Setae on—				
		First antenna	Second antenna		Mandible	
			Endopod	Exopod	Endopod	Exopod
Nauplius I	1+1	6	4	5	3	3
Nauplius II	1+1	7	4	6	3	3
Nauplius III	4+4	7	5	7	3	3
Nauplius IV	6+6	7	6	8	3	3
Nauplius V	7+7	9	7	9	3	3
Protozoea I	7+7	9	9	11	----------	--------

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APPENDIX 1

NOTES ON REARING

Trial 1

The first seabob to spawn viable eggs was caught October 7, 1959, with a 10-foot otter trawl 6 miles northeast of the Galveston Jetties in a depth of 5 fathoms. This female was returned to the laboratory and placed in a plastic barrel filled with sea water filtered through a plankton net. Thirteen hours later, eggs were found in the container. The eggs were pipetted from the container bottom and distributed among seven 4-liter beakers filled with water from the spawning container. These beakers were sampled for larvae periodically during the next 110 hours.

Hatching began shortly after introduction of the eggs into the beakers and continued for 2 days. As development proceeded, specimens of each instar were examined and preserved for future study. Water temperatures in the beakers ranged from 19.6° to 25.0° C. during the trial, and salinity measured 29.5°/oo. Mortality in all instars proved high, and no more than 40 specimens reached the Protozoea I stage.

At the conclusion of this trial, preliminary descriptions of each instar were begun. It soon became apparent, however, that too few specimens of Nauplius III and IV in good condition were available to complete the figures and descriptions.

Trials 2 to 6

Through the spring, summer, and fall of 1960 repeated attempts to rear seabob larvae failed. On five different occasions gravid females were captured and returned to the laboratory. Some aborted their eggs in gelatinous masses, while the eggs of others were round and smooth but proved nonviable. Sometimes viable eggs were spawne and appeared to develop normally for a time, onl to stop for no apparent reason. Destruction of t eggs by micro-organisms, chiefly bacteria an ciliates, frequently caused hatching failures. E tanglement of the larvae in detritus also serious hindered the rearing trials.

After each failure, efforts to improve conditio in the rearing containers were made. These i cluded: addition of antibiotics, irradiation wi ultraviolet light, filtration, centrifuging, and pr heating the medium to rid it of micro-organism Artificial sea water was tried as a medium als Despite these efforts, all rearing trials failed durin 1960.

Trial 7

On April 25, 1961, 2 dozen gravid female collected from 2 to 3 fathoms northeast of t Galveston Jetties, were returned to the recent completed circulating sea-water laboratory. He they were distributed among five small gla aquaria and three circular, wooden tanks, 4 fe in diameter and 3 feet deep. Water circulating the aquaria and two of the tanks was filtere through glass wool, then through a cellulose filte and finally irradiated with ultraviolet. The thi wooden tank received sea water filtered throug an 18-inch layer of coarse sand. Water ten perature ranged from 23.0° to 24.0° C., and salinit was 22.6°/oo.

Spawning took place in all the containers withi 6 hours after introduction of the females. Eg were siphoned from the spawning aquaria, di tributed among containers in which the treate r was circulated, and observed continuously. hing began approximately 10 hours after ning and continued for 41 hours. Although of the resulting larvae reached the protozoea during this trial, the additional nauplial mens obtained permitted completion of the larvae descriptions.

e following table, constructed from notes during the two successful trials, indicates vals between molts.

TABLE A-1.—*Chronological development of larvae*

	Hours after spawning	
	Trial 1	Trial 7
Nauplii well-developed and moving sporadically inside egg	11	11
Nauplius I first found	11½	12
Nauplius II	17	25
Nauplius III	51	28
Nauplius IV	55	44
Nauplius V	57	----------
Protozoea I	58	----------
Hatching ceased	32	41

UNDANCE, AGE, AND FECUNDITY OF SHAD, YORK RIVER, VA., 1953–59

By Paul R. Nichols [1] and William H. Massmann [2]
Fishery Research Biologists

ABSTRACT

**study of the American shad fishery of the York
, Va. during 1959 showed an estimated total catch
3,000 pounds, a fishing rate of 55.2 percent, and a
population of 839,000 pounds. Additional es-
tes of catch and effort were used to calculate
ng rate and population size for each year 1953
through 1958. Analyses of scales showed that most shad spawn at 3, 4, and 5 years of age and approximately 23 percent of the fish caught during the 1957–59 seasons had spawned the previous year. The number of ova produced by York River shad ranged from 169,000 to 436,000 per fish.**

ne commercial yield of American shad (*Alosa*
dissima) on the Atlantic coast declined from
ak of 50 million pounds in 1896 to 8 million
ıds in 1950. In 1950 the Bureau of Com-
ial Fisheries, acting as the primary research
cy of the Atlantic States Marine Fisheries
mission, began an investigation of the fishery
etermine causes for the decline, conditions
ring recovery, and management measures
ssary to obtain maximum continuing yields.
nce funds and personnel were not sufficient
study of all shad producing streams of the
ntic coast, it was necessary to limit the
stigation to certain areas each year. This
rt concerns the shad population of the York
r, Va. In this study the York, which includes
Pamunkey and Mattaponi Rivers, was termed
York River system.

uring the spring spawning run of 1959,
onnel of the Bureau of Commercial Fisheries
ogical Laboratory, Beaufort, N.C., in coopera-
with the Virginia Institute of Marine Science,
icester Point, Va., conducted an investigation
ie fishery to estimate total catch, fishing rate, total population entering the river for each year in which catch and effort data were available, and to obtain certain life history information.

LIFE HISTORY

American shad are the largest members of the herring family in the United States. They are anadromous, spending most of their life in the sea, but ascending coastal rivers to spawn. On the Atlantic coast, shad range from the St. Lawrence River, Canada, to the St. Johns River, Fla. Spawning migrations begin in Southern rivers as early as November and progressively later in Northern rivers. The number of eggs produced by females sampled from Atlantic coast rivers ranges from 116,400 to 659,000 (Lehman, 1953; Walburg, 1960). The young spend the first summer of life in the rivers and usually migrate to sea in the fall of the same year, at which time they are from 3 to 6 inches in length. In 3 to 6 years, they reach sexual maturity and return to the stream of origin to spawn.

Adult shad enter the York River as early as January, and the run usually continues until mid-May. It is during this time that they become available to the fishery. The bulk of the catch is usually made in a 6-week period from early March until mid-April. Massmann and Pacheco

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E.—Approved for publication July 16, 1962. Fishery Bulletin, Vol.
o. 1.

eau of Commercial Fisheries Biological Laboratory, Beaufort, N.C.
ginia Institute of Marine Science, Gloucester Point, Va.
tribution No. 130. Virginia Institute of Marine Science, Gloucester
Va.]

(1957), in a study of the relationship of water temperature and shad catch in Virginia, showed that the greatest catches were made at water temperatures ranging from 45° to 59° F., and that below 40° F. very few shad were caught. The major spawning areas in the Pamunkey River are 20 to 25 miles above West Point and in the Mattaponi River 15 to 20 miles above West Point (Massmann, 1952). York River shad normally do not die after spawning, and if they survive natural and fishing hazards, they return to spawn in successive years (Talbot and Sykes, 1958).

DESCRIPTION OF RIVER AND SHAD FISHERY

The York River is formed by the union of the Pamunkey and Mattaponi at West Point, Va. (fig. 1). It flows southeasterly for a distance of 28 miles and empties into Chesapeake Bay at Tue Point. In this study an imaginary line drawn between Tue Point and Guinea Marshes marks the mouth of the river. The Pamunkey is formed by the junction of North Anna and South Anna Rivers in central Virginia and flows approximately 100 miles to its union with the Mattaponi. The Mattaponi is formed by the Matta, the Po, and the Ni Rivers in northeastern Virginia and flows approximately 120 miles to unite with the Pamunkey. Tidal waters extend about 45 miles up the Pamunkey and 30 miles up the Mattaponi. The change from brackish to fresh water occurs from 5 to 10 miles above West Point in each river.

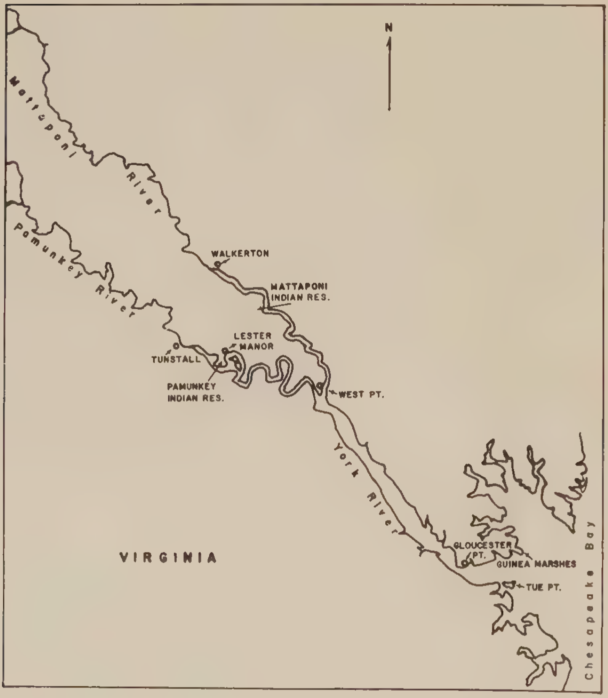


FIGURE 1.—York River system, Virginia.

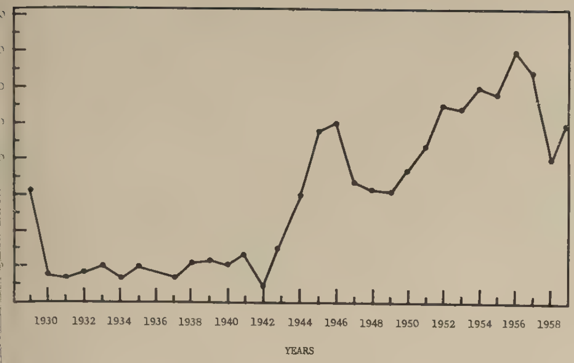
Stake gill, drift gill, pound, and fyke nets, and haul seines were the gears employed in the fishery, named in order of their importance as determined by pounds of fish taken. The locality and miles of river fished by each gear are shown in table 1. Stake gill nets fished in the York were suspended from poles, spaced about 20 feet apart, driven into the river bottom. These nets were fished continuously during the shad season and were lifted on high and low tides. Pound nets, haul seines, and fyke nets, also employed in the York, were fished from early spring until fall. After the shad season these gears were fished for other species. Drift gill nets employed in the Mattaponi and Pamunkey were fished during periods of high and low slack waters, which permitted about 3 hours fishing on each tide. Regulations established by the Virginia Commission of Fisheries licensed stake gill nets by 600-foot rows, limited the length of drift gill nets to 600 feet, and permitted the taking of shad from inlets and rivers during the period from October 16 to May 25. Because of navigational difficulties from the mouth of the river to West Point, the location fished by stationary gears was designated by the U.S. Army Corps of Engineers so that shipping channels were unobstructed.

TABLE 1.—*Water area and location of shad gear fished. York River system, 1959*

Water area	Gear	Miles of river	Location of area
York River	Pound net	6	Mouth of river to Gloucester Point.
York River	Haul seine	6	Mouth of river to Gloucester Point.
York River	Fyke net	20	Gloucester Point to West Point.
York River	Stake gill net	20	Gloucester Point to Wes Point.
Pamunkey River	Drift gill net	26	West Point to Tunstall.
Mattaponi River	Drift gill net	21	West Point to Walkerton.

STATISTICS OF THE FISHERY, 1929–59

Estimated shad catches in the York River system for years 1929 through 1959 are shown in figure 2. The annual yield was at a low level during the years 1930 through 1943, with the



RE 2.—Estimated shad catch, York River system, 1929–59.

t production of 23,800 pounds in 1936. After 3 the yield increased rapidly and was approxi- ely one-half million pounds by 1946. Then he following 3 years the catch declined to less 1 one-third million pounds, after which it n increased with a peak production of more 1 two-thirds million pounds in 1956. The 9 yield was more than that of 1958, but was than the catch for any of the years from 1953 ugh 1957.

atch statistics for the years 1929 through 1952 compiled by the Branch of Statistics of the eau of Commercial Fisheries,[3] those for 1953 ugh 1958 were estimated from logbook records cted by the Virginia Institute of Marine nce, and the 1959 data were obtained from the ent study.

o obtain the 1959 statistics a letter explaining study was mailed prior to the start of the on to each shad fisherman licensed on the k River system during 1958. A logbook was osed, and each fisherman was asked to record catch and effort each day. Biologists con- ed fishermen throughout the season to learn amount of each type of gear fished, to collect recovered from the tagging study conducted ltaneously with the statistical study, to urage the recording of catch and effort data, to help with the logbook records. At the end he season, all fishermen were contacted per- lly or by letter for logbook and tag returns. h and effort data were obtained for all nd-net, haul-seine, and fyke-net fishermen; ercent of the stake gill-net fishermen; and 56 ent of the drift gill-net fishermen. Total catch and effort for the gill-net fisheries were estimated from information obtained from the logbooks.

In 1959 the shad catch was reported in pounds and the effort recorded in number of nets fished each day. Number of nets fished each day was converted to net days, i.e., a pound net, haul seine, or fyke net-day was defined as one net fished for 1 day, and a stake and drift gill net-day was defined as 100 linear yards of net fished for 1 day. The estimated total catch and effort for all gears was 463,124 pounds in 24,112 net-days (table 2). Gill nets accounted for 94 percent of the total catch and 84 percent of the total effort.

TABLE 2.—*Estimated total catch and effort of shad fishery, York River system, 1959*

Gear	Nets fished	Effort	Catch		
			Males	Females	Total
	Number	*Net-days*	*Pounds*	*Pounds*	*Pounds*
Pound nets	20	1, 204	6, 679	8, 809	15, 488
Haul seines	2	20	700	800	1, 500
Fyke nets	64	2, 575	6, 591	4, 114	10, 705
Stake gill nets	5, 003	11, 308	58, 975	164, 209	223, 184
Drift gill nets	524	9, 005	98, 247	114, 000	212, 247
Total	5, 613	24, 112	171, 192	291, 932	463, 124

Logbook data, collected each season from 1953 to 1958 by the Virginia Institute of Marine Science, were made available for this study. Analysis of the logbook data, kept by the same fishermen each year, accounted for approximately 25 percent of the total catch and effort in 1959. Catch per unit of effort for the major gears remained relatively constant from 1953 to 1959. Data for the years 1953 through 1958 were therefore adjusted, based on the results of the 1959 study. The estimated catch and effort by gear for 1953 through 1959 are given in table 3.

TAGGING STUDY, 1959

During the 1959 season, a tagging and recovery program was conducted to estimate the rate of exploitation and the size of the shad population. Fish for marking were obtained from pound nets located near the mouth of the river in the vicinity of Tue Point. Tagging began on March 9 and was discontinued on May 3 when the run terminated. During this period 842 shad were marked with streamer tags, similar to those used by Davis (1959). The tag was a red plastic disk, with an identification number on one side

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ublished data. Bureau of Commercial Fisheries Biological Labora-
eaufort, N.C.

TABLE 3.—*Estimated shad catch and effort by gear, York River system, 1953–59*

Year	Pound net		Haul seine		Fyke net		Stake gill net		Drift gill net		Total catch
	Effort	Catch	Effort	Catch	Effort	Catch	Effort	Catch	Effort	Catch	
	Net-days	*Pounds*	*Net-days*	*Pounds*	*Net-days*	*Pounds*	*Net-days*	*Pounds*	*Net-days*	*Pounds*	*Thousands of pounds*
1953	46	4, 544	23	17, 764	6, 102	16, 451	12, 614	231, 727	9, 801	282, 069	55
1954	138	4, 544	69	13, 525	3, 821	20, 911	8, 980	300, 139	9, 064	262, 709	60
1955	49	3, 416	25	8, 115	3, 274	9, 639	11, 509	251, 484	8, 005	264, 923	53
1956	79	5, 404	40	8, 115	5, 372	14, 483	10, 843	398, 114	7, 706	290, 392	71
1957	75	4, 866	38	7, 304	4, 339	15, 393	10, 060	399, 844	6, 845	211, 033	63
1958	77	4, 555	39	5, 000	4, 247	14, 500	8, 777	215, 289	6, 328	146, 772	38
1959	1, 204	15, 488	20	1, 500	2, 575	10, 705	11, 308	223, 184	9, 005	212, 247	46

and return address and reward notice on the other, to which a loop of nylon twine was tied. The nylon loop was fastened under the origin of the dorsal fin, which allowed the disk to trail immediately behind the fin, not interfering appreciably with the normal activity of the fish.

Of the total number of fish tagged, 118 were recaptured from areas outside the York River system. Of these, 105 were recaptured in the Chesapeake Bay system, 4 in North Carolina, 4 off the New England coast, 3 in the Hudson River, and 2 tags were returned from fish markets in Philadelphia, Pa. Approximately 89 percent of the outside returns were recaptured in the Chesapeake Bay system. On the basis of previous studies in the bay by Walburg (1955) and Walburg and Sykes (1957), an outside fishing rate of 50 percent was estimated. Therefore, 236 shad tagged at the mouth of York River were considered as en route to other river systems and were subtracted from the number tagged. Using criteria established by Talbot and Sykes (1958), one tagged fish recaptured in Chesapeake Bay on June 8 was not included since it was not known whether this fish had spawned in the York. This left 605 tagged fish which entered the York River for the purpose of spawing. Of this total, 334 were recaptured: 173 in the York, 104 in the Pamunkey, and 57 in the Mattaponi.

To obtain valid estimates from our tagging program certain factors, which may be sources of error, must be examined and their consequences satisfied (Ricker, 1958).

(1) *Differential mortality.*—Extra mortality among the tagged fish, either as a direct result of the tag or indirectly from effects of exertion by the fish during capture and handling incidental to the marking operation, may result in a biased fishing rate and population estimate. Sykes (1951) successfully handled and moved adult fish for distances up to 95 miles, and they remained alive and active for some time after transfer. This was considered as adequate demonstration that shad can survive rigorous handling. Atkinson (1951) handled and held adult shad in experimental ponds for several weeks without appreciable mortality. During the present experiment, only fish in apparent good physical condition and those unabraded in the process of capture were marked. Every precaution was taken to prevent damage to the fish which could result in extra mortality from handling and marking.

(2) *Loss of tags by detachment.*—The tag and attachments are completely durable. Approximately 25 percent of the catches were examined for scars that would be left from detachment, and no evidence was found of nonpermanent attachment. No unattached tags were reported taken in the nets. Therefore, loss of tags by detachment was considered negligible.

(3) *Tagged fish more, or less, vulnerable to fishing than untagged fish.*—If tags made shad more vulnerable to fishing, a higher proportion of tagged to untagged fish would occur in the catch of the lower fishery than at locations further upstream. The proportion of tagged to untagged fish in the lower river catch was no greater than that found further upstream, and the rate of capture of tagged fish was approximately the same as that for untagged fish by each gear at the different locations. Pound nets and haul seines in the lower York took 3.7 percent of the total catch and 3.6 of the tagged fish recaptured. Fyke and stake gill nets employed in the upper York took 50.5 percent of the total catch and 48.2 percent of the tagged fish recaptured, and drift gill nets operated in the tributaries took 45.8 percent of the total catch and 48.2 percent of the tagged fish recaptured.

The point of insertion of the tag and type treamer used did not make the tagged fish more ulnerable to gill nets than untagged fish by eason of the tag entangling in the net. For the rst 5 weeks the weekly rate of recapture of agged fish and untagged fish indicated no diference in behavior of the fish, i.e., in the first eek 6.9 percent of the recaptures of tagged fish as made and 5.0 percent of the catch was made; n the second week the rate was 10.0 and 10.0; n the third week 15.0 and 15.1; in the fourth eek 20.0 and 20.0; and in the fifth week 24.4 nd 25.0.

Length measurements of shad caught in previous easons indicated that fish more than 14.3 inches rk length were liable to capture by all types of ear fished in the York system; therefore, no fish ss than this length were tagged. Fish less than his length were of no market value and were reeased or eliminated from the catch.

A chi-square test between catch and number of ags recovered by gear type showed that no tag electivity occurred within the size range tagged

$$(\chi^2=2.16;\ P=0.71).$$

(4) *Nonreturn of tags.*—Each fisherman was ontacted prior to the season to acquaint him with he tagging program. Then four biologists canassed the fishery daily throughout the entire eason for tag returns. At the end of the season ach fisherman was contacted to collect the reovered tags. The number of recaptured tags not ecovered probably would not appreciably bias he estimates.

(5) *Nonrandom distribution of tagged fish.*—arked fish were randomly distributed throughut the population being sampled by tagging niformly throughout the season from the first ear the fish encounter in the river, so that, as early as possible, tags were affixed in proportion o the number of shad migrating upstream. Close greement of the ratio of tagged to untagged fish aken in the tributaries (spawning grounds) proided evidence that tagging was random with reect to the destination of the shad.

Based on the tagging study the calculated fishg rate was 55.2 percent and the estimated poption size 838,892 pounds. To determine the tal population of shad entering the river in 1959, hapman's (1948) formula $N=\frac{nt}{s}$ was used, where N=total population, n=total catch (463,124 pounds), t=number of fish tagged (605), and s=number of tagged fish recaptured (334). Escapement from the fishery was 375,768 pounds. The limits within which the population estimate fell with 95 percent confidence were 900,000 and 800,000 pounds (Chapman, 1948).

GEAR EFFICIENCY AND STANDARDIZATION OF EFFORT

To determine total fishing effort in standard units required to make the 1959 shad catch, the fishing efficiency of the various gears must be determined. Fishing efficiency was defined as the ability of one unit of effort to remove a certain fraction of the available population in a specified interval of time. The method used to determine fishing efficiency was similar to that used by Talbot (1954), in which fishing gears fish different areas. As previously noted, however, pound nets and haul seines fished the lower river, stake gill and fyke nets fished the central section of the river, and drift gill nets were fished upriver. Before the efficiency of gears fished in different areas could be determined, it was necessary to combine the effort of those gears fishing in the same area.

The unweighted average catch per unit of effort by haul seines 1953 through 1959 was found to be 4.60 times that of pound nets, and the unweighted average catch per unit of effort by fyke nets 1953 through 1959 was 0.12 times that of stake gill nets. Haul-seine effort was converted to pound-net effort by multiplying haul-seine effort (table 3) by 4.60. Fyke-net effort was converted to stake gill-net effort by multiplying fyke-net effort (table 3) by 0.12. The effort and catch of these gears as combined will henceforth be included under pound nets and stake gill nets as given in table 4. We now have three standardized gears, each fishing a different area of river.

Table 4.—*Estimated catch and effort, York River system, 1953–59*

Year	Pound nets		Stake gill nets		Drift gill nets		Total	
	Effort	Catch	Effort	Catch	Effort	Catch	Effort	Catch
	Net-days	*Pounds*	*Net-days*	*Pounds*	*Net-days*	*Pounds*	*Net-days*	*Thousands of pounds*
1953	152	22, 308	13, 346	248, 178	9, 801	282, 069	23, 299	552
1954	455	18, 069	9, 438	321, 050	9, 064	262, 709	18, 957	602
1955	164	11, 531	11, 902	261, 123	8, 005	264, 923	20, 071	538
1956	263	13, 519	11, 488	412, 597	7, 706	290, 392	19, 457	716
1957	249	12, 170	10, 581	415, 237	6, 845	211, 033	17, 675	638
1958	256	9, 555	9, 287	229, 789	6, 328	146, 772	15, 871	386
1959	1, 296	16, 988	11, 617	233, 889	9, 005	212, 247	21, 918	463

The fishing efficiency of each gear, designated as p, was determined using Fredin's (1954) formula $q^n N=E$,[4] from which we derive

$$\log q=\frac{\log E/N}{n}$$

where $q=1-p$, E=escapement from a fishery, N=size of run available to a fishery, and n=units of effort in net-days. From our tagging and recovery program, the estimated size of run (N) available to pound nets was 838,892 pounds. The catch (c) was 16,988 pounds; hence, the escapement (E) from these nets was 821,904 pounds. The units of effort (n) were 1,296. Solving the above equation, the q value obtained was 0.999984. Since $p=1-q$, the fishing efficiency of pound nets was 0.000016. Shad that escaped the pound nets were available to the stake gill nets. The fish available to this gear were 821,904 pounds, of which 233,889 pounds were removed by 11,617 units of effort. Solving the equation, the q value obtained was 0.999971, and therefore $p=0.000029$. Fish that escaped both pound and stake gill nets were available to the drift gill nets. The shad available to these nets amounted to 588,015 pounds, of which 212,247 pounds were removed by 9,005 units of effort. Solving the equation for this gear, the q value obtained was 0.999950, and therefore $p=0.000050$.

After a measure of the fishing efficiency of each gear was determined, it was possible to convert fishing effort in net-days to standard-fishing-unit days (Talbot, 1954). A standard-fishing-unit (s.f.u.) day was defined as 100 linear yards of drift gill net fished for 1 day. The fishing efficiency of the pound net and stake gill net was 0.32 and 0.58 that of the drift gill net. This was determined by dividing the fishing efficiency of the pound and stake gill net by that of the drift gill net. Fishing effort of pound nets and stake gill nets was converted to standard-fishing-units by multiplying the effort of each net in net-days by these conversion factors. Total catch, effort, and catch per unit of effort are listed in table 5.

TABLE 5.—*Estimated effort in standard-fishing-unit (s.f.u.) days by gear, York River system, 1953–59*

Year	Effort in s.f.u. days				Total catch	Catch per s.f.u. day
	Pound net	Stake gill net	Drift gill net	Total		
					Thousands of pounds	*Pounds*
1953	49	7,741	9,801	17,591	552	31.4
1954	146	5,474	9,064	14.684	602	41.0
1955	52	6,903	8,005	14,960	538	36.0
1956	84	6,663	7,706	14,453	716	49.5
1957	80	6,137	6,845	13,062	638	48.8
1958	82	5,386	6,328	11,796	386	32.7
1959	415	6,738	9,305	16,158	463	28.6

ESTIMATE OF POPULATION SIZE, 1953–59

The relative population of shad entering the river can be estimated for any year in which catch and effort statistics are available provided: (1) fishing effort is uniform throughout the season, (2) fishing efficiency remains constant within and between seasons, and (3) the migration pattern of the fish is similar each year (Ricker, 1940).

Available records indicated that fishing was carried out essentially in the same areas using the same types of gear as when the fishery was first investigated in 1953. The main part of the run lasted about 6 weeks, and fishermen fished every day possible. Fishing effort and efficiency, therefore, tended to be uniform throughout the season and between seasons. Water level, turbidity, or water temperature may have affected migration routes within the river for short periods of time, but not necessarily over the entire season. Even though the length of runs and time of fish passage through the fishing areas may have varied from year to year, there was no indication that the York River shad, once in the river, migrated differently in different seasons. Based on these assertions, it was assumed that the above provisions given by Ricker were satisfied for this fishery.

The population for each year 1953–59 was estimated by Talbot's (1954) formula:

$$N=\frac{C}{1-q^n}$$

where C=catch, $q=1-p$, and n=fishing effort in standard-fishing-unit days. The estimated population for these years is listed in table 6. Fishing rate ranged from 58.3 percent in 1953 to 44.4 percent in 1958. The population fluctuated between 1.4 million pounds in 1956 and 0.8 million pounds in 1959. Escapement reached a peak of 0.7 million pounds in 1957 compared to a low of 0.4 million pounds in 1959.

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[4] Modification of Beverton and Holt's (1957) model for estimating relative fishing power of vessels and standardization of commercial statistics of fishing effort.

TABLE 6.—*Estimated shad population parameters, York River system, 1953–59*

Year	Catch	Effort	Fishing rate	Total population	Escapement
	Thousands of pounds	*s.f.u. days*	*Percent*	*Thousands of pounds*	*Thousands of pounds*
1953	552	17, 591	58. 3	947	395
1954	602	14, 684	51. 8	1, 162	560
1955	538	14, 960	52. 5	1, 025	487
1956	716	14, 453	51. 3	1, 396	680
1957	638	13, 062	47. 8	1, 335	697
1958	386	11, 796	44. 4	869	483
1959	463	16, 158	55. 2	839	376

AGE COMPOSITION

Each season 1957 through 1959 scales were collected from fish taken in stake and drift gill nets. Plastic impressions were made of two symmetrical scales from each fish, and age was determined using the method described by Cating (1953).

The scales were read for age at capture, age at first spawning, and number of times previously spawned (table 7). Shad entering the river for the first time were predominately 3- and 4-year-old males and 4- and 5-year-old females. Approximately 23 percent of the fish in the samples (14.8 percent of the females and 37.6 percent of the males) had spawned the previous year. The small percentage of fish returning to spawn the second or more times is probably due to exploitation outside the river and to ocean mortality. In 1952 Walburg and Sykes (1957) found that 27 percent of the James River shad and 17 percent of the Potomac River shad had spawned previously.

TABLE 7.—*Age composition of shad, York River system, 1957–59*

Group	1957		1958		1959	
	Females	Males	Females	Males	Females	Males
Total age at capture:						
2 years	2	3	0	0	0	0
3 years	7	21	5	23	19	35
4 years	71	62	63	73	398	190
5 years	77	25	80	34	154	99
6 years	15	2	27	2	25	21
7 years	2	2	9	1	3	4
8 years	0	0	0	0	0	1
Total	174	115	184	133	599	350
Age at first spawning:						
2 years	2	3	0	0	0	0
3 years	14	35	12	42	32	128
4 years	89	65	83	77	447	211
5 years	67	12	78	14	112	11
6 years	2	0	11	0	8	0
Total	174	115	184	133	599	350
Number of times previously spawned:						
0	137	88	152	92	526	193
1 time	29	18	21	24	58	83
2 times	5	8	7	15	15	65
3 times	3	0	3	2	0	5
4 times	0	1	1	0	0	4
Total	174	115	184	133	599	350
Total	289		317		949	

The size by sex was determined. Mean weight was 2.3 pounds for males and 3.2 pounds for females. Fork length ranged from 12.6 to 17.3 inches for males and 14.0 to 20.0 inches for females.

OVA PRODUCTION

Ova production was determined by sampling the ovaries from 18 females captured during April 1959. Fish were taken from stake gill nets located in the lower section of the river approximately 50 miles below the spawning ground. Fish were chosen selectively so that different size and age groups were represented. They ranged from 14.9 to 19.0 inches in fork length, 2.1 to 5.0 pounds in weight, and 4 to 7 years in age. Ova estimates were made using the method described by Lehman (1953) and modified by Davis (1957). Ova counts ranged from 169,000 to 436,000 (table 8).

TABLE 8.—*Estimated ova production of 18 female shad, York River, 1959*

Specimen No.	Fork length	Total weight	Weight of ovaries	Mean number of ova	Estimated total ova
	Inches	*Ounces*	*Grams*	*Per gram*	*Thousands*
1	14. 9	34	120. 5	2, 090	252
2	15. 2	37	133. 2	1, 696	226
3	15. 4	43	141. 4	1, 488	210
4	15. 7	39	217. 7	778	169
5	15. 8	39	146. 1	1, 412	206
6	16. 0	42	126. 0	1, 542	194
7	16. 0	44	155. 4	1, 956	304
8	16. 8	48	214. 0	966	207
9	16. 8	53	164. 4	1, 698	279
10	17. 0	52	224. 6	1, 322	297
11	17. 3	59	210. 4	1, 169	246
12	17. 5	56	164. 4	1, 540	253
13	17. 9	64	213. 1	1, 977	421
14	18. 2	65	233. 3	1, 675	391
15	18. 3	67	280. 8	1, 318	370
16	18. 5	73	303. 5	1, 436	436
17	18. 7	62	220. 3	1, 636	360
18	19. 0	80	391. 7	914	358

The relation between ova production and length, or weight, or age of the York River shad is shown in figure 3. Linear regressions showed that there was an increase in ova production with increase in each of these variables within the size and age range sampled. Ova production was somewhat more highly correlated with weight ($r=0.820$) than with length ($r=0.795$) or with age ($r=0.740$).

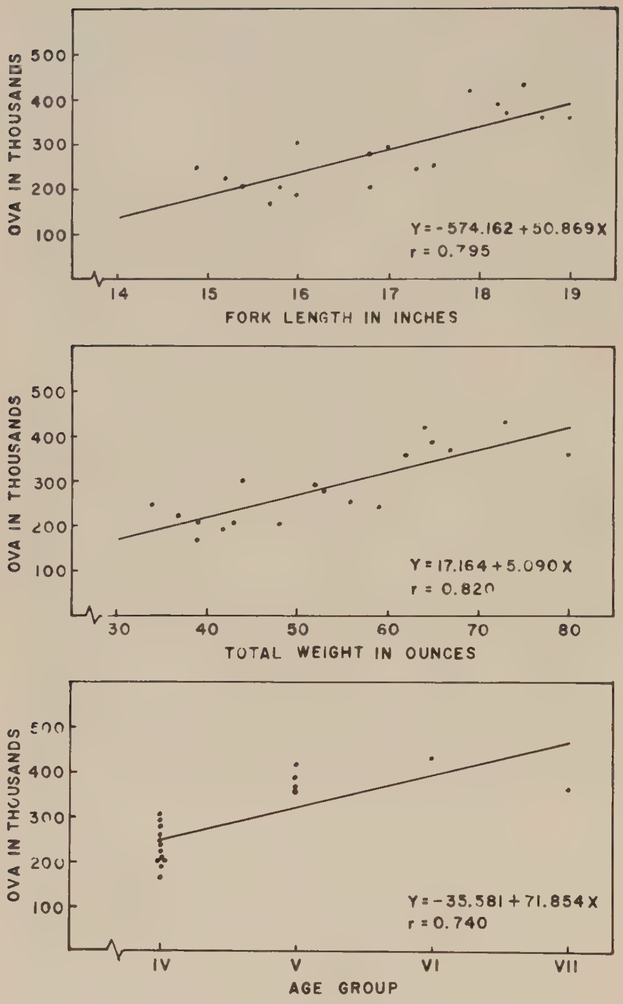

Figure 3.—Relation between ova production and length, weight, and age in female shad, York River, 1959.

SUMMARY AND CONCLUSIONS

The Bureau of Commercial Fisheries Biological Laboratory, Beaufort, N.C., in cooperation with the Virginia Institute of Marine Science, Gloucester Point, Va., conducted a study on the shad population of the York River system in 1959 as part of an investigation of the Atlantic coast shad fishery. This river system includes the York, Pamunkey, and Mattaponi Rivers. The purposes were to determine total catch, fishing rate, population entering the river system for each year in which catch and effort data were available, and certain life history information.

Estimated total catch in 1959 was 463,000 pounds, of which gill nets accounted for 94 percent. The fishing rate was estimated to be 55.2 percent, estimated population 839,000 pounds, and spawning escapement 376,000 pounds. Ninety-five percent confidence limits on the population estimate were 900,000 and 800,000 pounds. With catch and effort statistics available for the years 1953 through 1958, it was possible to estimate population size, fishing rate, and spawning escapement for each of these years, based on information obtained during the 1959 study. Estimates showed that the commercial yield reached a peak of 716,000 pounds in 1956 and a low of 386,000 pounds in 1958; fishing rate ranged from 44.4 percent in 1958 to 58.3 percent in 1953; population reached a peak 1.4 million pounds in 1956 compared to a low of 0.8 million pounds in 1959; and escapement reached an estimated high of 0.7 million pounds in 1957 compared to a low of 0.4 million pounds in 1959.

Shad that entered the York River for the first time were predominantly 3- and 4-year-old males and 4- and 5-year-old females. Twenty-three percent of the catch had spawned the previous year. Ova production ranged from 169,000 to 436,000, and linear regressions showed an increase in number of eggs with an increase in weight, length, and age of the fish.

In this investigation, a method was presented to estimate the shad population of the York River system, provided catch and effort statistics are collected each year. Population estimates were calculated on this shad fishery for seven consecutive years. The value of this study for scientific management of the fishery will not be realized, however, until population estimates have been obtained for an additional number of years.

ACKNOWLEDGMENTS

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COD GROUPS IN THE NEW ENGLAND AREA

By John P. Wise, *Fishery Research Biologist*
BUREAU OF COMMERCIAL FISHERIES

ABSTRACT

Indications from previous tagging experiments since 897 result from tagging 2,794 cod by the author from 955 to 1959, and evidence from other sources indicate our groups of cod in the New England area: (1) The od of the offshore banks, (2) the cod of the Gulf of aine, (3) the cod of southern New England and the South Channel, and (4) the New Jersey coastal cod which spend the summer in southern New England.

It is suggested that the first three groups are stocks not genetically separate, while the New Jersey fish are a genetic subpopulation. Within all of these groups, except the last, there is a tendency for the larger fish to move permanently to the north and east.

Although cod, *Gadus morhua* L., are widely istributed on both sides of the North Atlantic, o cod marked on the European coast has ever een recovered on the coast of North America, or vice versa. Many cod tagged at Iceland fig. 1) have been recaptured at West Greenland, ut there are only one or two records of fish agged at Iceland recaptured as far west as Newoundland waters. Many years of marking xperiments by Europeans and North Americans, upported by studies of meristic characters Schmidt, 1930), have conclusively demonstrated e lack of interchange between European cod nd those of the North American coast.

Concentrating, then, on the cod of the western tlantic, there have been a considerable number f important studies which serve to point out the eparation of various groups found here.

Templeman (1953) considers the cod of Labraor separate from those of West Greenland, basing is conclusions chiefly on vertebral counts. In consideration of growth rates, age at sexual aturity, and parasite infestation, he concludes rther that the Labrador cod are distinct from e Newfoundland and Grand Bank fish. He oints out (p. 64) that, "Apart from fish tagged on St. Pierre Bank it is very unusual for any fish tagged in Newfoundland to cross the Laurentian Channel to the Nova Scotia Banks or to the southern side of the Gulf of St. Lawrence."

Martin (1953), in discussing the major groundfish stocks of Subdivision 4 of the Convention Area of the International Commission for the Northwest Atlantic Fisheries (roughly the Nova Scotian and Gulf of St. Lawrence regions), states (p. 57), "The deep-water Fundian Channel between Georges and Browns Banks and the still deeper Laurentian Channel between St. Pierre Bank and Banquereau are barriers to the movement of cod. Except for occasional movements of individual cod across these channels we may consider that the cod populations along the Nova Scotian coast, in the western Gulf of St. Lawrence, and on the Nova Scotian offshore banks are resident in Subarea 4." As to western Nova Scotia, he reports that, "Resident populations show restricted movement and do not mix with eastern or offshore cod."

The data published by McKenzie (1956) show that from about 20,000 cod tagged along the Nova Scotia and Gulf of St. Lawrence coasts and offshore banks from 1926 to 1940, there were many hundreds of returns east of longitude 65° W.

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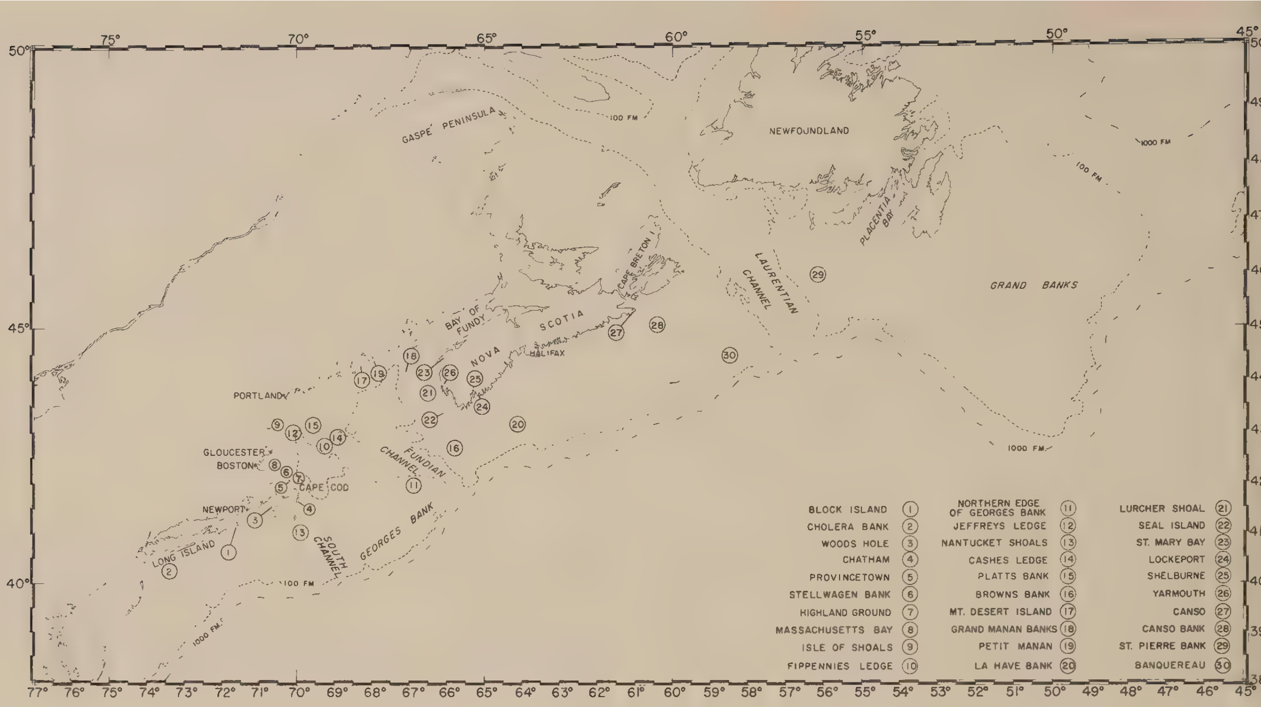
GASPE PENINSULA
NEWFOUNDLAND
100 FM
1000 FM
PLACENTIA BAY
LAURENTIAN CHANNEL
GRAND BANKS
CAPE BRETON
NOVA SCOTIA
BAY OF FUNDY
HALIFAX
PORTLAND
GLOUCESTER
BOSTON
CAPE COD
NEWPORT
LONG ISLAND
FUNDIAN CHANNEL
GEORGES BANK
SOUTH CHANNEL
BLOCK ISLAND ①
CHOLERA BANK ②
WOODS HOLE ③
CHATHAM ④
PROVINCETOWN ⑤
STELLWAGEN BANK ⑥
HIGHLAND GROUND ⑦
MASSACHUSETTS BAY ⑧
ISLE OF SHOALS ⑨
FIPPENNIES LEDGE ⑩
NORTHERN EDGE OF GEORGES BANK ⑪
JEFFREYS LEDGE ⑫
NANTUCKET SHOALS ⑬
CASHES LEDGE ⑭
PLATTS BANK ⑮
BROWNS BANK ⑯
MT. DESERT ISLAND ⑰
GRAND MANAN BANKS ⑱
PETIT MANAN ⑲
LA HAVE BANK ⑳
LURCHER SHOAL ㉑
SEAL ISLAND ㉒
ST. MARY BAY ㉓
LOCKEPORT ㉔
SHELBURNE ㉕
YARMOUTH ㉖
CANSO ㉗
CANSO BANK ㉘
ST. PIERRE BANK ㉙
BANQUEREAU ㉚

FIGURE 1.—The western North Atlantic area.

However, only about a dozen came from west of 65°, that is from New England waters as considered here.

For purposes of this study, New England waters have been rather liberally defined as those parts of the Atlantic Ocean north of latitude 40° N. and west of longitude 65° W. With this and the results above in mind, it is evident that the New England cod are generally distinct from American cod living to the north and east and may be treated as one or more discrete ecological units. The only exception is the southern stock of cod which infiltrates the New England area in summer (Wise, 1958).

This report presents the results of recent (since 1955) marking experiments in New England waters, taking into consideration, however, the results of previous experiments and other evidence where applicable, to provide the best description possible of the relations of the cod groups in the New England area. (The words "group" and "stock" are used here as defined by Marr (1957).)

PREVIOUS TAGGING EXPERIMENTS

Although cod had been tagged in the northeastern Atlantic as early as 1888, it was not until 1897 that any were marked on the American side. During the 1920's and early 1930's, under the stimulus of the newly formed North American Council on Fishery Investigations, considerable numbers were marked in New England waters by Canadian and United States biologists. A few publications were issued as a result of this work, but unfortunately many of the experiments were never reported in detail in any permanent form, and the original records are either lost or destroyed. Many of the summary reports are ambiguous and contradictory, particularly as regards the number of fish tagged and recaptured, and the exact locations of tagging and recapture. I have consulted some of the men who engaged in these operations, but after nearly 40 years their memories of dates, places, and numbers are understandably imprecise. Insofar as possible, the following summary, based, unless otherwise stated, on Higgins (1929, 1930, 1931a, 1931b, 1932, 1933, 1934, 1936), Rich (1925, 1926), Schroeder (1928, 1930), and the reports of the North American Council (1932, 1935), presents the most complete reconstruction of all experiments previous to December 1955 in New England waters. The results and conclusions drawn from them, the development and evolution of tags and methods, were also reconstructed from the same sources, and the latter is presented as a separate section.

TAGGING EXPERIMENTS AND RESULTS FROM 1897 TO 1955

Table 1 shows in summary form all tagging pre- ous to 1955. Obviously these experiments were vastly different scopes, and the results in terms returns were extremely variable, both in num- rs and percentage, from a fraction of 1 percent numbers approaching one-half of the fish re- rned, for instance, the 1953 Canadian experi- ent yielding more than 40 percent by the spring 1955.

In retrospect, however, they may be grouped th their results in the following way:

1. Southern Nova Scotia and Browns Bank. On e basis of the Canadian work from 1924 to 1927, cKenzie (1934, 1956) concluded that the fish ound Shelburne were essentially stationary, ile those at Seal Island showed a movement stward during summer and returned in winter. e U.S. tagging on Browns Bank in 1927 was not ccessful; the Canadian work from 1926 to 1930, the Bay of Fundy, was never reported in detail, r was the U.S. work on Browns in 1928 and 1930. shore tagging in 1938 and 1939 yielded less than returns, most of these nearby, but 1 from eorges Bank.

Most of the large numbers of cod reported recaptured by McCracken (1956) from his work off Lockeport, Nova Scotia, in the summer of 1953 were taken more or less locally, a few from the banks directly offshore, about 20 well to the northeast, and 7 from Georges Bank and vicinity.

2. Gulf of Maine. From 1923 to 1932, the U.S. Bureau of Fisheries marked fish in the Gulf of Maine, with a concentration of the work around Mount Desert Island and on Platts Bank. Although good numbers of fish were marked, probably more than 6,000, and the percentages of returns up to about 20 percent in some cases, no report was ever published in detail, and the only available summary occurs in the Proceedings of the North American Council on Fishery Investigations (1932, p. 12), that there was "very little intermingling between the more southern population and the cod of the gulf of Maine, of Georges bank and of Nova Scotia . . . . In general the fish of the Mt. Desert ground have been found, by recapture, to remain chiefly stationary in the locality, the few recorded journeys . . . being nearly all eastward . . . ."

3. Georges Bank. The U.S. Bureau of Fisheries marked cod on Georges Bank from 1926 intermit-

TABLE 1.—*Summary of all cod tagging experiments in New England waters previous to 1955*

[See text for sources not given here]

Year	Area	Number tagged	By whom tagged
–1901 (winters)	Woods Hole and vicinity	4,019	H. M. Smith.[1]
(April–October)	Stellwagen Bank	12	W. C. Schroeder.
	Mouth of Bay of Fundy	56	Canadian biologists.
(July–October)	Massachusetts Bay		W. C. Schroeder.
	Platts Bank	218	
	Mount Desert Island		
	Petit Manan, Maine to Southern Mass.		W. C. Schroeder.
	Mount Desert Island (April–May)	1,611	
	Platts Bank (June–July)	604	
(August)	Georges Bank	1,016	W. C. Schroeder.
–1928 (winters)	Woods Hole	1,859	W. C. Schroeder.[2]
–1929	Southern New England	23,555	W. C. Schroeder.[2]
	Cholera Bank	300	
	Southern New Jersey	884	
(summer)	Shelburne, Nova Scotia	4,011	Biological Board of Canada.
	Yarmouth, Nova Scotia	28	
(June)	Seal Island, Nova Scotia	1,840	Biological Board of Canada.[3]
	Georges Bank	477	U.S. Bureau of Fisheries.
	Browns Bank	904	
	Platts Bank (April–October)	79	
	Cashes Ledge (September–October)	321	
	Massachusetts coast, north of Cape Cod, off New Hampshire and Maine, on or near Browns and Georges Banks.	1,285	U.S. Bureau of Fisheries.
–1930	Bay of Fundy	61	Biological Board of Canada.[3]
(April–October)	Mount Desert, Georges Bank, Browns Bank, Cashes Ledge, Platts Bank, Nantucket Shoals.		U.S. Bureau of Fisheries.
	Mount Desert	1,199	U.S. Bureau of Fisheries.
	Woods Hole (January)	340	
	Nantucket Shoals (August)	172	
	Mount Desert	1,481	U.S. Bureau of Fisheries.
	Woods Hole (January)	304	
	Mouth of Bay of Fundy	13	Biological Board of Canada.[3]
(April)	St. Mary Bay	83	Biological Board of Canada.[3]
(summer)	Lockeport, Nova Scotia	1,804	Fisheries Research Board of Canada.[4]

Smith, 1902.

Schroeder, 1930, which includes some 1,184 fish tagged to the south of area.

[3] McKenzie, 1934, 1956.

[4] McCracken, 1956.

tently to 1930, probably something on the order of 2,000 fish in all, but the records show only 6 recaptures, 3 of them on the bank.

4. Woods Hole. Smith (1902) and Schroeder (1930) report basically similar results from releasing with marks during the winters of 1897–1901 and 1925–28, nearly 6,000 of the cod which had been held at Woods Hole as a source of eggs and milt for the hatchery in operation during that period. Most were recaptured locally, some to the north and east, and some as far south as southern New Jersey. Schroeder incorporated the results of this work in his conclusions about the cod of southern New England (see below). The results of the 1931 and 1932 work were never published.

5. Nantucket Shoals and southward. Schroeder (1930) reports in considerable detail on the tagging from 1923 to 1929 of nearly 25,000 fish, mostly on Nantucket Shoals, and also as far south as southern New Jersey. His most important conclusions from these experiments, taken together with length frequency studies and sclerite counts of the scales were:

(*a*) The stock of cod living on Nantucket Shoals is for the most part distinct from that living to the north and east of southern Massachusetts.

(*b*) A large part of this stock makes a fall migration to the Rhode Island-North Carolina region, where many spawn and most remain until spring (see Wise (1958) for another interpretation of this movement).

(*c*) Part of the cod living on Nantucket Shoals emigrate eastward to the Chatham-South Channel region during certain summers.

(*d*) The stock on Nantucket Shoals is recruited from younger fish from other regions, most of them from offshore grounds. When they reach about 75 cm. in length, they tend to move off the shoals, perhaps to the offshore banks.

TAGS AND METHODS

Smith (1902) used numbered pieces of sheet copper about three-fourths of an inch by one-fourth of an inch, with a hole in one end through which a fine copper wire was passed. These tags were fastened at various places on the fish, but mostly the upper part of the caudal fin, near the peduncle. About 3.5 percent of the cod were recaptured.

Later, Bureau of Fisheries investigators used a metal tag similar to a cattle ear tag, and in the beginning attached it exclusively to the uppe
part of the caudal peduncle by means of speci
clamping pliers. Various metals were used exper
mentally: silver, aluminum, copper, silver-plate
copper, but monel was finally chosen as bes
The vast majority of all cod marked between 190
and the termination of the experiments in 193
were marked with this tag and in this manner.

It was estimated early in the work, howeve
that as high as 60 percent of these tags were she
by the fish within the first year. Later th
estimate was revised upward, based partially o
recaptures by research vessels of fish which bo
unmistakable marks of having been tagged. B
ginning in October 1927, some fish of 75 cm. or le
were marked with the same tag clamped on th
lower jaw between the dentary and articula
bones, in the hope that these tags would not b
so easily lost. Fish thus marked, howeve
yielded no higher percentage of return, and i
1928 this method was abandoned.

Some tags made of duralumin, a hard alloy
aluminum, were used after 1929, since it was fe
that this metal had all the virtues of monel with
out its weight.

In 1930, a pair of celluloid discs, resemblin
the Scottish plaice mark, was used with conside
able promise. Half of the cod released at Woo
Hole in 1932 were marked with celluloid discs o
the tail and half on the opercle; within 11 month
8.5 percent of the opercle-tagged cod had bee
recaptured vs. 5.3 percent of the caudally tagge
In the same year, experiments were carried ou
with celluloid strips inserted into the coelo
during the Mount Desert experiments. The
showed some promise of being more permane
than anything used previously, but the U.S. co
investigations were not carried out long enoug
thereafter to establish conclusive results.

All of the Canadian work from 1924 throug
1939 was done with the monel tag described abov
In McCracken's (1956) tagging, he used this t
and also used red and white Petersen discs (o
of each color) attached on stainless steel wi
through the back of the fish, yellow discs attache
similarly, and Lea hydrostatic tags on a stainle
wire loop through the back. The red and whi
discs gave by far the best returns, more than
percent, the yellow discs over 50 percent. T
hydrostatic and strap tags were a poor third a

urth, with just above 30 percent each, vs. an
erall average of more than 40 percent.

RECENT TAGGING EXPERIMENTS

While marking experiments from 1955 through
59, like all such work, were somewhat oppor-
nistic, depending on weather, availability of
h for tagging, availability of research and com-
ercial vessel time, etc., in retrospect the coverage
the New England area was reasonably good.
ie experiments fall naturally into three geo-
aphic groups, offshore banks, Gulf of Maine,
d off southern New England. Table 2 gives a
mmary of the time and place of each of the
periments in this series, together with the
mber of fish tagged and the number and percent-
e returned. The percentages returned should
taken here as only the grossest indication of the success of a particular operation; the factors affecting these percentages have been taken up in some detail elsewhere[1] and will be considered briefly here.

BLE 2.—*Summary of cod tagging experiments, 1955–1959*

Place and time	Number tagged	Number returned	Percent returned
	OFFSHORE BANKS		
rges Bank:			
Dec. 1956	113	8	7.1
Mar.–Apr. 1957	434	66	15.2
Oct. 1957	51	2	3.9
Total	598	76	12.7
wns Bank:			
Mar. 1957	149	48	32.2
Oct. 1957	76	11	14.5
Total	225	59	26.2
	GULF OF MAINE		
hes Ledge:			
June–July 1956	114	11	9.6
Nov. 1957	50	5	10.0
eys Ledge:			
July 1956	20	3	15.0
Apr. 1959	4	0	0
tchers Island:			
July 1956	2	0	0
cher Shoal:			
Oct. 1957	7	1	14.3
nd Manan Banks:			
Oct.–Nov. 1957	232	7	3.0
pennies Ledge:			
Nov. 1957	7	0	0
Total	436	27	6.2
	SOUTHERN NEW ENGLAND		
vport, R.I.:			
Dec. 1955	59	7	11.9
tham, Mass.:			
Feb.–Mar. 1957	1,020	[1] 253	24.8
th Channel:			
Oct. 1957	177	13	7.3
hland Ground:			
Oct. 1957	237	27	11.4
Nov. 1958	42	4	9.5
Total	1,535	304	19.8
Grand total	2,794	466	16.7

Actually 248 fish (253 returns) as 4 were caught after tagging, released caught again, of which 1 was caught, released, and caught again.

THE TAGS

The Lea tag has been described by Rounsefell and Everhart (1953). It consists basically of a small plastic tube, stopped at each end. Inside the tube, which is waterproof, directions for the finder are printed on a roll of thin paper. Although this tag is often fastened to the dorsal musculature of the fish with a wire bridle, in this work the tags were affixed to a monel chain which was in turn fastened to a plastic tab inserted in the coelom as described by Wise (1958).

Rounsefell and Everhart also give a good description of the Petersen tag and its development. The discs used in these experiments were of the type they describe as developed by Nesbit, and were bright yellow. The method of attachment was one worked out by scientists of the St. Andrews Biological Station of the Fishery Research Board of Canada, i.e., on stainless-steel wire through the dorsal musculature. A No. 12 hypodermic needle on a pin vise handle was passed through the muscles just in front of the first dorsal fin and the first interspinous bone. The stainless-steel wire bearing the numbered disc was then pushed through the bore of the needle, the needle withdrawn, another disc placed over the free end of the wire, and the wire cut to length and knotted to hold the two discs firmly in place. This method differs from the one most often used by the Canadians in that they place the tag between the first and second dorsal fins, with the wire passing between the interspinous bones.

A very few cod in these experiments were marked with plastic "spaghetti" tags through the dorsal musculature.

HANDLING METHODS

When tagging cod from a trap, the fish were removed by hand or by dip net from the pocket of the trap, as it was dried up, to a small floating live-car. These fish were taken one at a time from the live-car, tagged and measured, and released.

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[1] Wise, J. P. Factors affecting number and quality of returns from tagging cod with different tags and using different methods of capture in ICNAF Divisions 4X and 5Y in 1957. International Commission for the Northwest Atlantic Fisheries, North Atlantic Fish Marking Symposium. (In press.)

During long line operations, either from research or commercial vessels, fish which appeared not to have been seriously wounded by the hook or the other parts of the long line were gently released from the hook, immediately tagged and measured, and released.

The procedure used while otter trawling was quite different. The trawl net was towed on the bottom for periods of time varying from perhaps 20 minutes to an hour and a half; the time varied inversely with the abundance of fish. The objective was to obtain a reasonable number of fish which had been in the trawl for the shortest possible time.

At the end of the tow, the otter trawl was hauled back, the cod end hoisted aboard, and its contents dumped on deck. As quickly as possible the fish which appeared to be alive and in good condition were taken up from the deck by hand and placed in large wooden tanks of running sea water. The obviously dead or dying fish were culled from the tank, and sometimes when another tank was available the more promising specimens were transferred to a second tank. A measuring board was set up on the edge of the holding tank and fish were dip-netted as needed for tagging. Although some workers feel that it is profitable, where possible, to hold tagged fish in tanks for further culling of weak or dying individuals, this procedure was not followed in any of these operations.

Measurements were recorded usually to the nearest millimeter when the fish were less than 900 mm. in length, and to the nearest centimeter when the fish were larger. Because of haste or confusion, some fish were released before being measured. This happened perhaps 1 percent of the time.

RECOVERY METHODS

The message enclosed in the Lea tags and stamped on one of the pair of Petersen discs states that there is a reward for the return of the tag and gives the laboratory address. Although the tags are often returned directly by mail and the reward and information sent via return mail, agents of the laboratory stationed in New England ports have been empowered to pay the reward, a dollar, on the spot and to collect the pertinent information. In the same fashion, agents of the Fishery Research Board of Canada working unde a reciprocal agreement have collected tags and th Board has paid the reward. Since May 195 agents of the Fish and Wildlife Service have pai an additional dollar when the fish was returne with the tag. These arrangements have undoubtedly fostered getting a good percentage the tags recovered actually returned to the laboratory, more than if the initiative for sending the in were left entirely to the fishermen. In additio having the tags and often the fish received b trained technicians has improved the accuracy the information received, particularly concernin the length of the fish and its reaction to the tag

These recovery methods, not available t earlier investigators, doubtless account for som of the improvement in returns over pas experiments; how much would be difficult t estimate. On the other hand, previous worker particularly Schroeder, fished deliberately wit research vessels for tagged fish and caught som This was not done in the recent experiments.

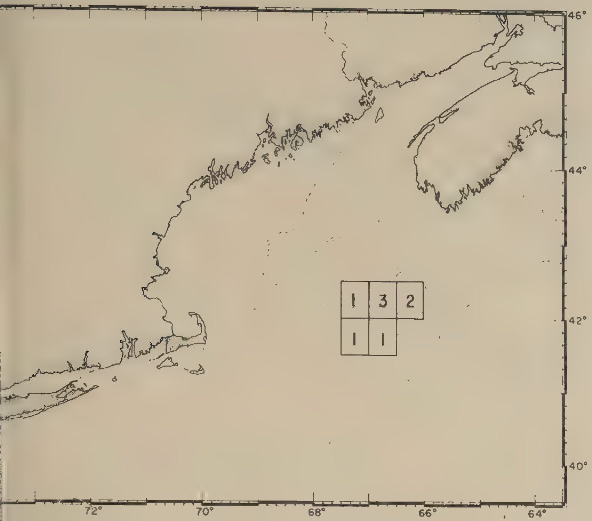
RESULTS

The details of the recent experiments, with exac locations and dates of tagging operations an recaptures are available for examination at th Bureau of Commercial Fisheries Biological Laboratory, Woods Hole, Mass. Below is a summary the results, grouped as the experiments are i table 2. The figures show the locations of recaptures, plotted usually by 26-week (half-year periods, in rectangles of 30 minutes of latitude b 30 minutes of longitude. Experiments whic yielded no returns and tags returned with insuff cient information were not considered in thi summary.

Recaptures from Tagging on Offshore Banks

1. Georges Bank, December 1956 (fig. 2 Only eight of the cod tagged were recaptured, a of them on Georges Bank and all within a yea No seasonal pattern is discernible in the recapture

2. Georges Bank, March–April 1957 (fig. 3 (a (b), (c), (d)). Through the summer and earl autumn, 20 were recaptured on Georges, 16 Browns and along the Nova Scotia shore as fa east as Halifax County (fig. 3(a)). The positio given in the upper left corner of this and subsequent figures gives the location of a return outsid the area of the chart. During the winter, fro



URE 2.—Returns from tagging cod on Georges Bank, December 1956.

tober until the next March (1958), 14 were urned from Georges Bank and 1 each from the ath and the northeast (fig. 3(b)). The next mmer, three were returned from Browns Bank l Nova Scotia (fig. 3(c)). During the winter l spring, three more were taken on Georges and o on Browns. In May and June, two were ght on the Nova Scotia shore (fig. 3(d)).

3. Georges Bank, October 1957. Only two fish re recaptured, and these were near where they l been tagged.

4. Browns Bank, March 1957. Through the nmer and early autumn, 13 were captured on or ar Browns and the near Nova Scotia shore, 3 m Georges, 3 from northern Nova Scotia, and rom the north shore of the Gaspé Peninsula g. 4(a)). During the winter and through the xt summer (1958), 19 were taken on the Nova otia banks and inshore, and 1 on Georges (fig.), 4(c)). Only a single fish was recaptured, on near Browns, until the next spring (1959) when ee were caught in the same region and one on orges. The following spring (1960), two were ght in the Browns-Nova Scotia area (fig. 4(d)).

5. Browns Bank, October 1957 (fig. 5). Until next April (1958) three were taken on Browns. om May through August two more were taken Browns and three on Georges. During the xt summer (1959), one was returned from owns, and the following spring (1960) one each Browns and Georges.

Recaptures from Tagging in the Gulf of Maine

1. Cashes Ledge, June–July 1956. Through the next spring (1957) 11 were caught in the Gulf of Maine and near the Massachusetts coast.

2. Cashes Ledge, November 1957. In June (1958) a fish was returned from Georges Bank. Later that year, single individuals were taken in the Gulf of Maine and near Provincetown, and during the following winter (1959), one fish was returned from Georges.

3. Jeffreys Ledge, July 1956 and April 1959. The only returns were from the 1956 tagging. Two were taken near the tagging location, and the next year (1957) one was caught off Rhode Island.

4. Lurcher Shoal, October 1957. One return, near the tagging location.

5. Grand Manan Banks, October–November 1957. Six returns, through March 1960, scattered from the tagging area to the Gulf of Maine and Georges and Browns Banks.

Recaptures From Tagging off Southern New England

1. Newport, R.I., December 1955 (fig. 6). Until February, 1957, 6 were taken off southern New England and Long Island. The summer following the tagging, a single fish was captured on western Georges Bank.

2. Chatham, Mass., February and March 1957 (fig. 7 (a), (b), (c), (d)). Within the first 6 months 122 recaptures were made in or very near the area (see footnote, table 2). Sixteen were taken north of the tagging area, in the Gulf of Maine, along the Maine coast, and as far as the Nova Scotia shore. Five were recaptured on eastern Georges Bank, and one on western Georges (fig. 7(a)). By March (1958), 19 more were taken in or near the tagging area, 3 just north of it, 1 on Georges Bank, 13 to the south and west as far as northern New Jersey (fig. 7(b)). From February through August (1958), 34 were taken in or near tagging area, 19 to the north as far as the Nova Scotia shore, 4 as far south as northern New Jersey, and and 1 on Georges Bank (fig. 7(c)). In August (1958) two were caught in the tagging area or just north of it, and another in January (1959). Later in 1959 another was taken in the Gulf of Maine (fig. 7(c)). The following summer (1960) two curious reports were sent in: a tag found on the beach in the Bay of Fundy and a similar return from Placentia Bay, Newfoundland.

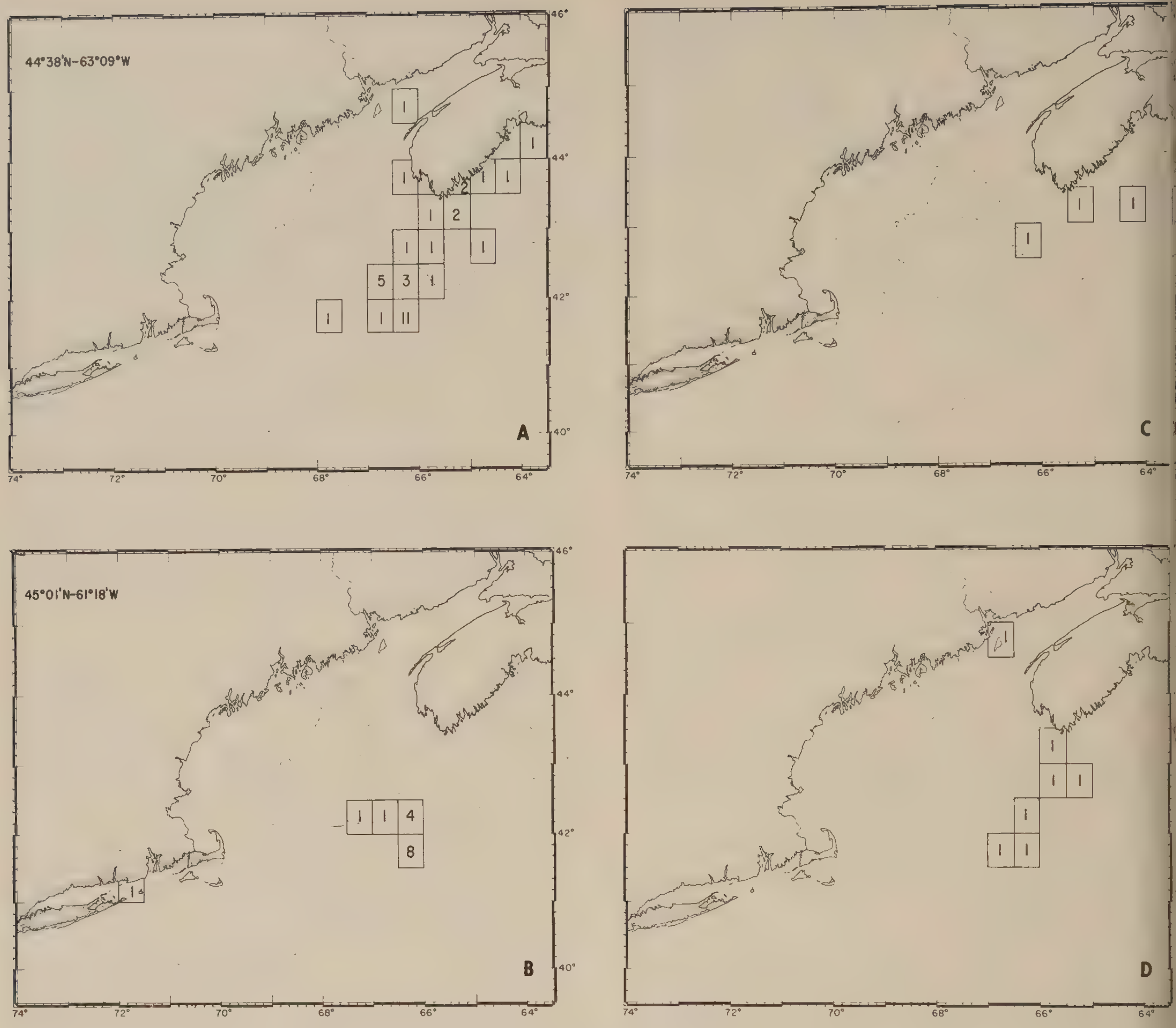


FIGURE 3.—Returns from tagging cod on Georges Bank, March–April 1957. (a) Within 26 weeks, (b) from 27 to weeks, (c) from 53 to 78 weeks, (d) from 79 to 116 weeks.

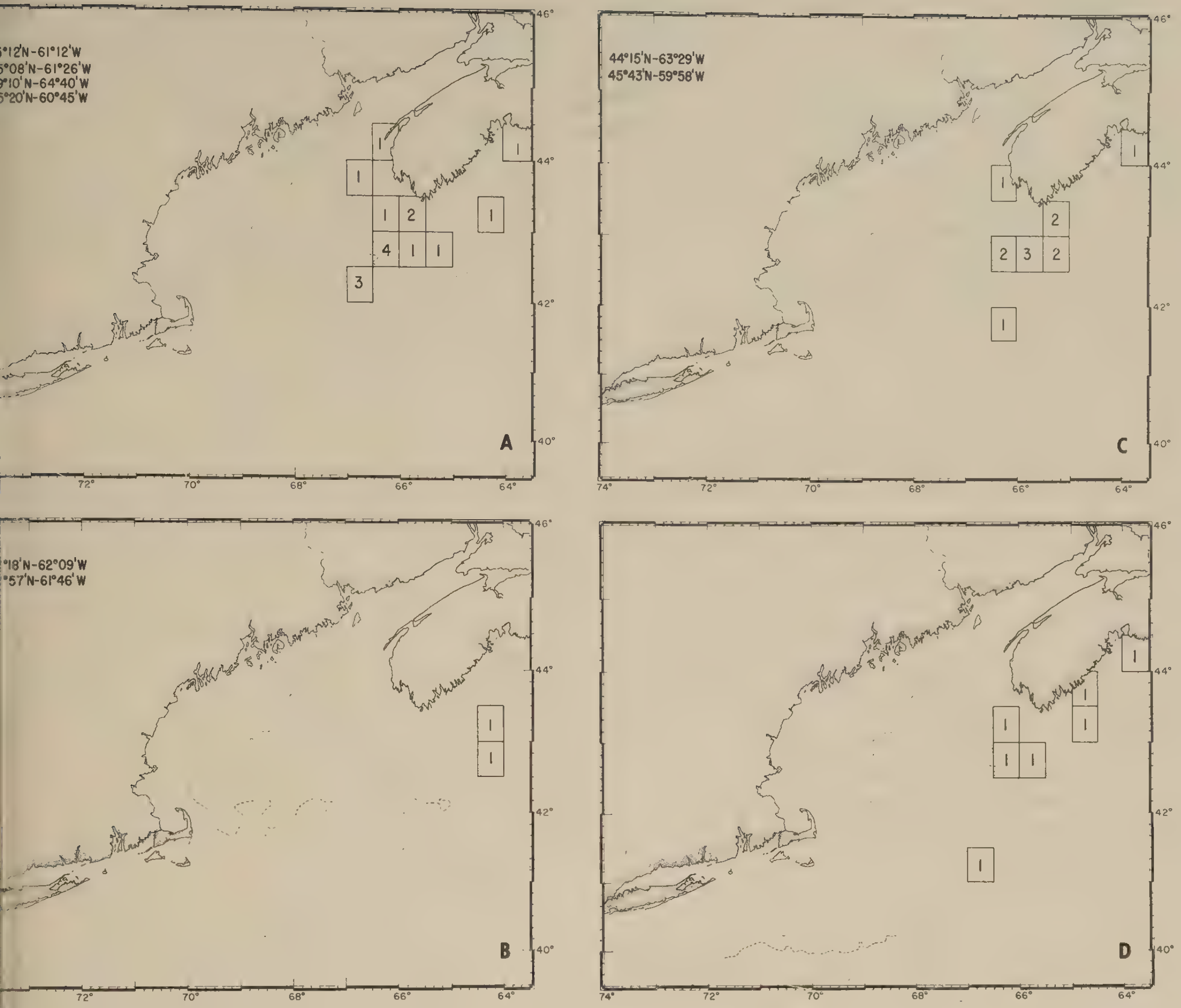
3. South Channel, October 1957 (fig. 8 (a), (b), (c)). (Figure 8 also shows the returns from the Highland Ground experiment of 1957.) Five fish were caught in or near the tagging area in the first year. During that same period, two were taken off Rhode Island, three in the Gulf of Maine, one just north of the tagging area, and one on Georges Bank (fig. 8 (a), (b)). Two years later, in July 1960, one was caught north of the tagging area.

4. Highland Ground, October 1957 (fig. 8 (a), (b), (c)). By February (1958), 9 fish had been recaptured in the general area of tagging and 1 to the south and west (fig. 8(a)). By September, four were taken near the area and two to th north of it (fig. 8(b)). By July (1959), four mor were taken near the area, and one to the sout (fig. 8(c)).

5. Highland Ground, November 1958. Onl four fish were recaptured, three of them in near the area and one in the Gulf of Maine.

Factors Affecting these Results

During 1957, cod captured both by otte trawling and long lining were marked with bot the Petersen disc through the dorsal muscles an with the modified Lea tag. Except on Brown Bank in March and at Chatham, Mass., alternat


°12'N-61°12'W
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°10'N-64°40'W
°20'N-60°45'W
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45°43'N-59°58'W
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°18'N-62°09'W
°57'N-61°46'W
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46°
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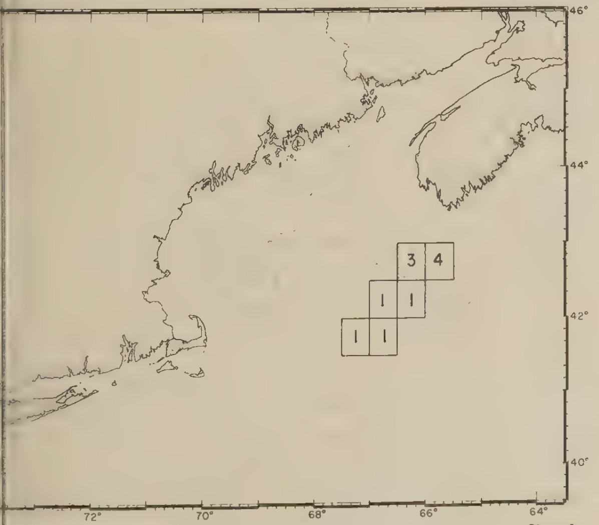
40°
74°
72°
70°
68°
66°
64°

URE 4.—Returns from tagging cod on Browns Bank, March 1957. (a) Within 26 weeks, (b) from 27 to 52 weeks (c) from 53 to 78 weeks, (d) from 79 to 163 weeks.


3
4
1
1
1
1
46°
44°
42°
40°
72°
70°
68°
66°
64°

URE 5.—Returns from tagging cod on Browns Bank, October 1957.

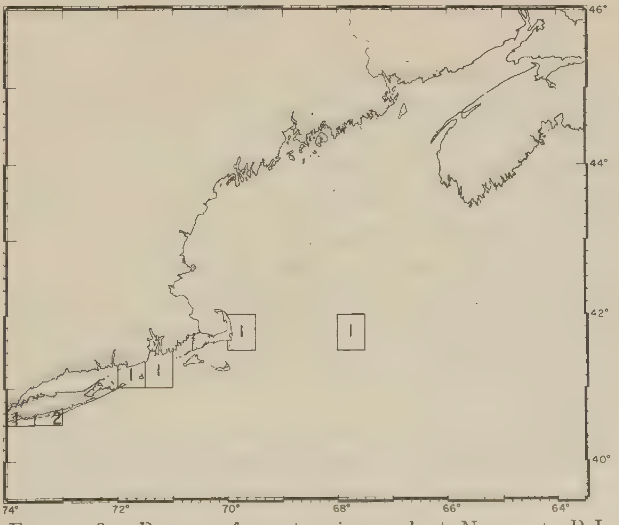

1
1
1
1
1
2
46°
44°
42°
40°
74°
72°
70°
68°
66°
64°

FIGURE 6.—Returns from tagging cod at Newport, R.I., December 1955.

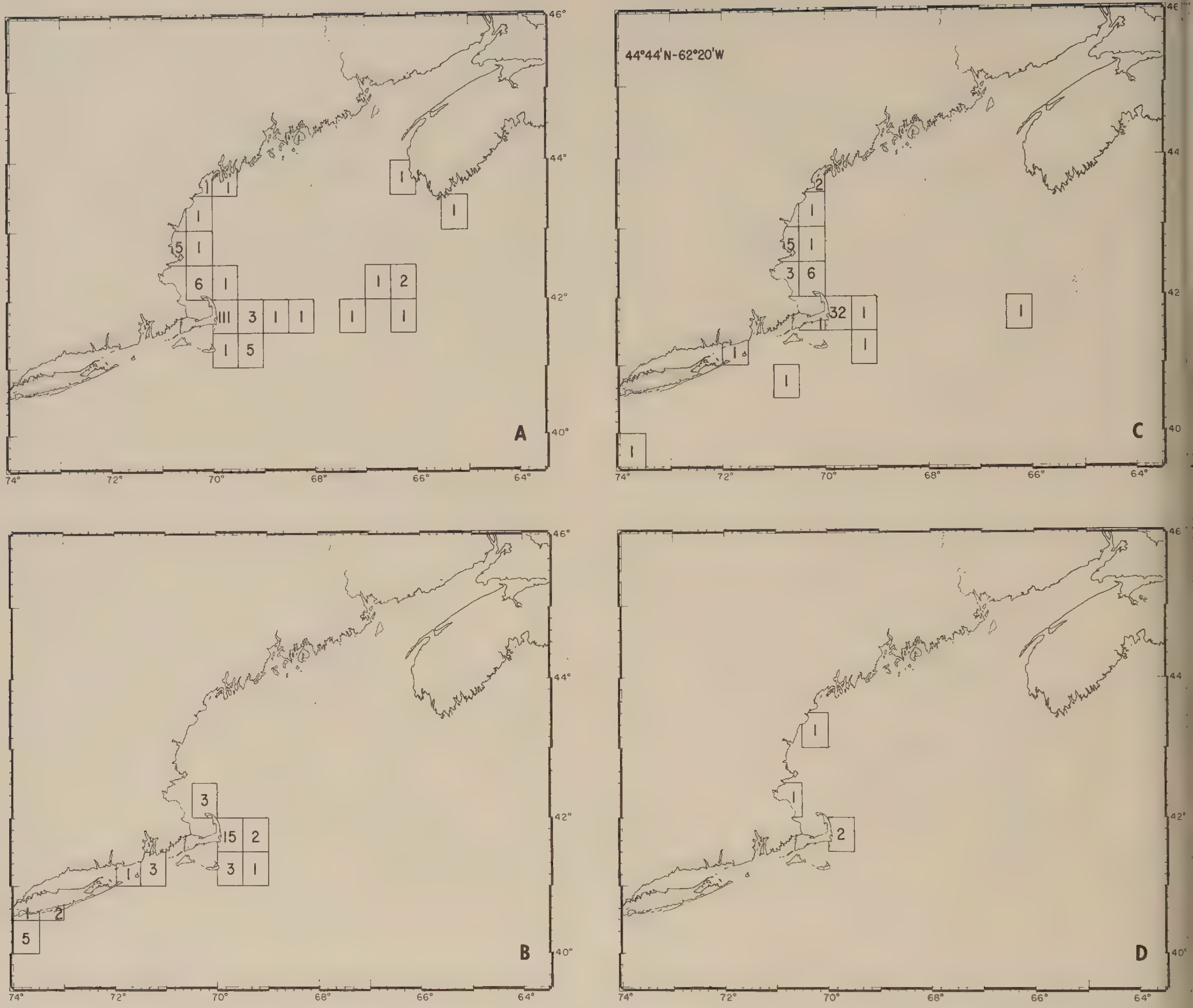


FIGURE 7.—Returns from tagging cod off Chatham, Mass., February–March 1957. (a) Within 26 weeks, (b) from 27 t 52 weeks, (c) from 53 to 78 weeks, (d) from 79 to 119 weeks.

tagging was carried out. The objective of this experiment was to evaluate the effectiveness of one tag in comparison with the other. The results have been reported elsewhere,[2] but it is worthwhile to summarize the most important of them here:

1. The advantage of the discs thus used over the Lea tags is approximately 2:1 in return percentages, although there is a suggestion in comparison with other work that the place of attachment may be more important than th tag per se.

2. The use of either of these marking method on otter trawl caught cod less than 40 cm. i length yields very low returns.

3. Long lining as a method of capture fo marking experiments gives better results, particularly for smaller fish.

4. All other things being equal, spring appear to be the best time of year for marking cod.

These considerations should be borne in min in considering the results of these experiment However, since the only conclusions drawn her are relative to distribution of fish and their move

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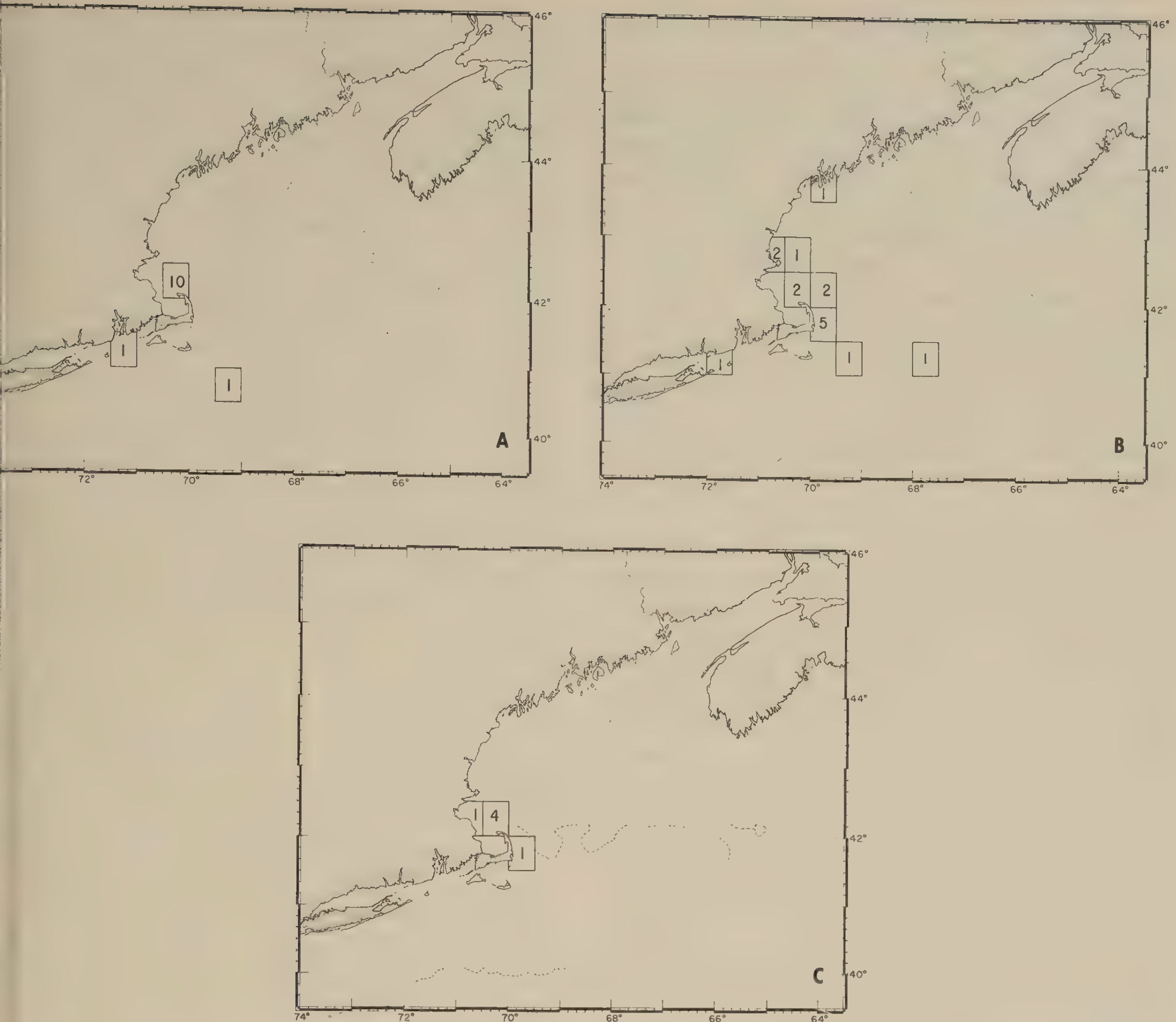
[2] Wise, J. P. Factors affecting number and quality of returns from tagging cod with different tags and using different methods of capture in ICNAF Divisions 4X and 5Y in 1957. International Commission for the Northwest Atlantic Fisheries, North Atlantic Fish Marking Symposium. (In press.)



GURE 8.—Returns from tagging cod in the South Channel and on the Highland Ground, October 1957. (a) Within 26 weeks, (b) from 27 to 52 weeks, (c) from 53 to 144 weeks.

ents, the effects are minor. It is only if these ata should be applied to estimation of population arameters that these variables would become nportant.

THER EVIDENCE OF DISCRETENESS OF GROUPS

THE COMMERCIAL LANDINGS

Although information about groups of fish erived from commercial landings must be intereted with caution, because of the selectivity various fishing gears and the culling practices fishermen, properly chosen data treated appropriately can often yield valuable information. For several years we have been collecting information on the length-frequency distribution of the landings of cod caught by otter trawl in New England. These have recently been published in sufficient detail to show differences in the catches in broad areas. The length-frequencies for 1957, 1958, and 1959 (Wise and Murray, 1959, 1960, 1961) show definite differences between the western Gulf of Maine and the Georges Bank-southern New England area. While the means and modes of the length distributions are somewhat variable, there is a definite tendency for a greater percentage of the landings from the Gulf of Maine to be composed of larger fish (above 80 cm.) than those from the more southerly area. If there is any difference in the nets used, it is that those in the Gulf have on the average somewhat smaller meshes. This could not produce the observed effect, as it has been shown experimentally that larger trawl meshes tend to catch a greater number of larger fish (Clark, McCracken, and Templeman, 1958). This length-frequency distribution alone is strong evidence against a free interchange of fish of all sizes between the two areas.

Indeed, there is evidence of a one-way movement of some of the larger fish from southern New England into the Gulf, and this doubtless contributes to the difference in size composition observed.

PARASITE STUDIES

Sherman and Wise (1961) studied the distribution of the long-lived copepod parasite of cod, *Lernaeocera branchialis*, in the New England area. We found heavy infestations, on the order of 20 percent, in the northern coastal region of the Gulf of Maine and moderate infestation, about 10 percent, in the central Gulf. We interpreted this as meaning that mixing between groups of fish in these areas occurs regularly. On Georges Bank and in the South Channel the infestation was much lower, less than 2 percent. This was taken to mean that there was little mixing between these and the Gulf fish. A sample of migrating cod taken off Rhode Island when they were on their way to the New Jersey coast in autumn had no *Lernaeocera* parasites.

MERISTIC STUDIES

Schmidt (1930) published counts of the number of vertebrae and number of rays in the second dorsal fin of cod from various Atlantic areas. He found large, statistically significant, differences between the cod of Nantucket Shoals, Mount Desert Island, and Grand Manan Banks. While these characters are somewhat variable with time, there were greater differences between the vertebral counts of cod from Nantucket Shoals and Mount Desert Island than there were between those of Mount Desert Island in different years. Grand Manan Banks fish were shown as different from either in one year, but only different from Nantucket Shoals in another.

CONCLUSIONS

The cod of the offshore coastal banks and of southwestern Nova Scotia coastal waters are relatively independent of any other groups in the New England area. There is, however, considerable movement within the group. Fish tagged on Georges Bank are most often caught on Georges Bank, but frequently turn up on Browns Bank and to the eastward in following summers. Fish tagged on Browns Bank are caught mainly on Browns Bank, but also to the eastward in following summers (consideration must be given to the small vessel fisheries of the Nova Scotia coast where fishing is prosecuted more heavily in summer than at any other time of year). Some Browns Bank fish cross over to Georges, but not nearly as large a percentage as cross the Fundian Channel in the other direction. Although a few fish from Georges and Browns are caught occasionally in the Bay of Fundy, only a single individual tagged offshore turned up near the shore of the New England States.

The cod of the waters north of a line between Provincetown, Mass., and the Northern Edge of Georges, and west of Nova Scotia, that is the Gulf of Maine proper, did not yield as high a percentage of returns as did the other groups in these experiments, and even when time of tagging and gear differences are taken into consideration, this is in itself a hint of their relative isolation. There is a considerable movement of some of the larger fish from southern New England into the area, probably in summer, but most of the fish tagged in the region and later recaught were caught within it, the majority of these not far from where they had been marked. A few leave the area, probably via a northern route around the southwestern part of Nova Scotia, and join the fish on the offshore banks. But the returns from current experiments, taken together with results of previous experiments and the high but variable infestation rates with the parasite *Lernaeocera branchialis*, indicate that there are several more or less discrete groups within the Gulf, intermingling with each other to some extent, but far less with fish outside the Gulf, particularly those of the offshore banks.

The cod of southern New England seem the most mobile of all. A great many tagged in the area are recaught in the area, even after considerable periods of time. Some individuals have en repeatedly recaught near where they were gged. There is, however, a definite tendency r some to wander to the south and westward ring the winter when hydrographic conditions e favorable. They do not go as far, though, as ose fish which return to the New Jersey coast to awn and which are the mainstay of the winter hery there.

During the summer, the fish of southern New ngland are augmented by the New Jersey cod, hile at the same time some of the larger ones ork their way north along the Massachusetts and aine shores, and a few even go as far as Nova otia. It seems doubtful, based on extensive mmer tagging experiments in the Gulf, in the 20's, that many of these fish return to southern ew England, particularly those which penetrate far as the coasts of Maine and Nova Scotia.

Thus, in the light of all evidence to date, there e four major groups of cod in the New England ea, all perhaps, and one certainly, divided into bgroups:

1. The cod of the offshore banks, (Georges and rowns) closely related to the fish of the south- estern Nova Scotia coast.
2. The cod of the Gulf of Maine, probably vided into many subgroups, and receiving con- derable recruitment from the south.
3. The cod of southern New England and the outh Channel.
4. The New Jersey coastal cod, which spend rt of the year mingled to a greater or lesser egree with the southern New England fish.

DISCUSSION

Consideration of the topography and hydrog- phy of the region shows that the distribution of e fish outlined above is consistent with the ysical features of their environment. A line awn along the 68th meridian separates the off- ore and southern Nova Scotia fish from the more shore groups; this is a line which runs through close to the important physical barriers of the ep mud bottoms of the central basin of the Gulf Maine, the extreme shoals of central Georges ank, and the relatively barren southern edge of e bank. Only around the narrow northern shelf the Gulf does this line cross suitable bottom for d, and all evidence points to this being the most kely path for what little interchange does take ace.

Within the Gulf the suitable areas are cut up and patchy, the isobaths meander, the bottom is varied, and these factors doubtlessly foster the subdivision of the Gulf fish into several groups. As Cape Cod is approached from the north, the shelf becomes constricted near Provincetown, forming a bottleneck and limiting effective intercommunication of the Gulf fish with the southern New England group.

South and west of Nantucket Shoals, hydrography plays the most important part in the distribution of the fish. In summer the area is uninhabitable by cod, and the New Jersey fish move north to spend the summer with the southern New England fish. As fall approaches and water temperatures drop, the New Jersey fish migrate back to their spawning grounds, while some of the southern New England fish spread out over suitable bottom along the Rhode Island and Long Island shores.

There is evident in the tag returns from nearly all areas, however, a general movement of fish which cannot be accounted for by anything ordinarily thought of as migration; a tendency for fish which move any considerable distance from where they were tagged to move to the north and/or east. This has been noted previously, first by Schroeder (1930), and later in the Proceedings of the North American Council (1935, p. 15), referring to tagging experiments conducted on the Maine coast, ". . . a noticeable scattering of fish takes place north-eastward to the Bay of Fundy-Nova Scotia region. . . ." (See also quote from the same publication above.) However, when the data on tagging experiments in the northeastern part of the New England area and those from the Canadian coast outside of the area are considered, there appears to be no movement of "Canadian" cod of comparable magnitude in the opposite direction. McKenzie (1956) reports many hundreds of returns from about 20,000 cod tagged along the Canadian Atlantic coast, but only a dozen of these came from New England waters. McCracken's (1956) report of tagging near Lockeport mentions the recapture of more than 700 fish, but only 7 of these came from Georges Bank and vicinity. Contrast these results with those reported above from New England waters where from several experiments a good number of cod were recaptured along the Nova Scotia coast. An attempt has been made to treat this movement quantitatively (Wise, 1959).

Of course, this effect could be produced by a fishing intensity increasing from the southwestern part of the New England and Nova Scotia area to the northeastern. This is not the case, however, for when the number of days fished per year by all gears except scallop dredges and harpoons (International Commission for the Northwest Atlantic Fisheries 1959) is considered, it is seen to decrease proceeding north and east, roughly:

	Days
Subdivision 5Z	24, 000
Subdivision 5Y	14, 000
Subdivision 4X	2, 000
Subdivision 4W	5, 000
Subdivision 4Vs	200

Whether any or all of the groups defined above are genetically self-sustaining subpopulations, or stocks which display nonheritable differences induced by environment is open to question. The movement of the pelagic eggs and larvae of cod, inferred from the nontidal drift of the surface waters, would generally be to the south and west through the area, promoting mixing in this direction, while the movement of larger fish to the north and east would tend to counteract this to some degree. Of course the size of the fish which appear to emigrate (Wise, 1959) is such that it appears likely that they would have spawned one or more times before they move. Thus, as an hypothesis, it is suggested that the first three groups, those of New England proper, are stocks, not genetically separate, while the New Jersey fish are a genetic subpopulation because of the geographic and hydrographic isolation of their spawning grounds. More detailed studies of morphometric and meristic characters of these four groups should shed considerable light on the question.

ACKNOWLEDGMENTS

Grateful acknowledgment must be made to A. C. Jensen, J. R. Clark, and other biologists and aids who assisted in tagging or who occasionally tagged fish when, for one reason or another, I was unable to do so, and to the skippers and crews of the *Albatross III*, *T–79*, and *Alice and Nancy*, without whom this work could not have been done. Special mention should go to David Ryder, owner-skipper of the *Alice and Nancy*, who cooperated in tagging, and later released tagged fish he had caught after recording their numbers. Careful record-keeping ashore by S. L. Cogswell and detailed checking of records by Mrs. H. E. Murray assisted immeasurably.

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ISTINGUISHING TUNA SPECIES BY IMMUNOCHEMICAL METHODS

By George J. Ridgway, *Biochemist*
Bureau of Commercial Fisheries

ABSTRACT

Interspecies differences in the sera of adult tuna lbacore, *Thunnus alalunga;* yellowfin, *Thunnus al- cares*; bigeye tuna, *Thunnus obesus:* skipjack, *Katsu- nus pelamis;* little tunny (wavyback skipjack), *uthynnus yaito;* and dogtooth tuna, *Gymnosarda ıda*) were demonstrated by double diffusion precipitation with antisera produced in rabbits. Studies of the soluble antigens extractable from the flesh of tuna were complicated by spontaneous precipitation. It was possible, however, to distinguish skipjack tuna from albacore and yellowfin by means of immunodiffusion of extractable tissue antigens.

The tunas, an economically and biologically ajor group of marine fishes, have been the sub- ct of considerable study by fishery scientists. ne of the most perplexing problems in these udies has been the identification of larval forms these fishes. Work on various aspects of this oblem using morphological and paper chroma- graphic methods has been presented by Walter . Matsumoto (1958, 1959, and 1960), who has scussed at considerable length the ultimate jectives and the difficulties of such research.

Because of difficulties in application of morpho- gical methods, due partly to the lack of known venile materials from some of the species, an dependent approach to this problem was needed supplement and check the results of the morpho- gical research. At the suggestion of Albert ster we made a preliminary study of the appli- bility of some immunochemical methods we have ed extensively in our salmon investigations. nce our time and facilities were largely com- tted to salmon research, our tuna studies were dertaken on a restricted scale and with limited jectives. These objectives were to determine ther differences could be detected in the serum antigens of adult tuna which were characteristic of the species. If these objectives could be accomplished, it was considered that it would be reasonable to use appropriate immunological methods for attacking the much more difficult problems involved in identification of the larval forms.

Our preliminary studies, which were carried out over a considerable period as material and time became available, indicated that there were detectable interspecific differences in the serum antigens of adult tuna. Financial support in 1960 from the Bureau's Biological Laboratory, Honolulu, enabled us to make a more complete study of many of the antisera we had prepared and also to make a preliminary study of the soluble antigens of adult tuna flesh.

This paper describes our studies on interspecific differences in the serum antigens of adult tuna. Similar studies on albacore, bigeye, and yellowfin tunas, reaching essentially the same conclusions, have been reported by Suzuki and Morio (1959). Charles Matsumoto had the primary responsibility for our soluble flesh antigen studies and is preparing a manuscript describing them; consequently, only a summary of the most important aspects of our research on these anti-

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ore.—Approved for publication August 27, 1962.

gens is presented. Finally, I have made recommendations concerning the direction that future immunochemical or serological research on this problem should take, in light of the results we and others have obtained, and taking into account certain other important factors.

BACKGROUND

The use of immunological methods for the identification of species is based on the specificity of antigen-antibody reaction. Knowledge of this specificity is general, since we know that immunity for one disease will not protect us when we are exposed to another.

Nuttall (1904) established that animal species can be distinguished by the specificity of characteristic antigens present in their serum. He also established that the degree of overlapping or cross reactivity in the specificity of the serum antigens of animals closely paralleled their taxonomic relationships. Many immunologists have subsequently used and extended these findings. Probably the most important studies are those of Irwin (1947) and his associates. They studied the antigenic constitution of the sera of species, species hybrids, and backcross hybrids of pigeons and doves, and demonstrated that the specificites of individual serum antigens were under direct genetic control. Thus, antigenic differences that we find between species can be considered direct consequences of the genetic differences between species.

METHODS AND MATERIALS

THE DOUBLE DIFFUSION PRECIPITIN ANALYSIS METHOD

Throughout this research we have used a modification of the Ouchterlony method of double diffusion precipitin analysis, exactly as described in another paper from this laboratory (Ridgway, Klontz, and Matsumoto, 1961). Since we described this method completely in that paper and it has been fully treated elsewhere in the literature (Ouchterlony, 1958) only a brief description will be given here. The method consists of allowing an antigen solution and an antiserum to diffuse toward each other through a semisolid medium containing a suitable concentration of saline or buffer and a preservative.[1] Where the molecules of a given antigen meet their specific antibodies in an optimal ratio of concentrations, a line of precipitation will form. Since the position of this line is dependent on the diffusion rates and initial concentrations of the antigen and its specific antibody and since these will vary between separate components, a separate line can form for each antigen-antibody system present. When two antigen solutions diffuse side by side toward a single antiserum the lines for identical antigens will fuse while those for unrelated antigens will cross.

Thus we have a system which allows us to separate out and study the reactions of individual antigens in a complex mixture and to compare the antigenic composition of one preparation with that of other preparations.

Photographic records of all of our tests were made as described in a previous publication (Klontz, Ridgway, and Wilson, 1960).

PRODUCTION OF ANTISERA

Antisera were prepared in rabbits in two different ways. One method consisted of emulsifying 2.5 ml. of pooled sera from several individuals of a given tuna species with 2.5 ml. Difco complete Freund's adjuvant and injecting the emulsion in several regional lymph node sites. After 15 days the rabbits were bled on 3 successive days. After a rest of 1 month, the animals were restimulated by two intraperitoneal injections of 0.25 ml. of serum and bled 4, 5, and 6 days later.

The second method used to produce antisera consisted of giving five to nine intraperitoneal injections of 0.25 to 0.5 ml. of pooled serum and bleeding on the fifth, sixth, and seventh days after the last injection. After 2 to 3 weeks rest, the rabbits were restimulated by two intraperitoneal injections of 0.25 ml. pooled serum and bled 4, 5, and 6 days later. The best antisera were obtained with the latter method. We also prepared several antisera in chickens by giving three intraperitoneal injections of 0.25 ml. pooled albacore serum at 4-day intervals and bleeding 5 days after the last injection. Although potent antibodies were detectable by the usual precipitin method we were unable to obtain useful results with these antisera in double diffusion tests.

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[1] The medium we use has the following composition: Difco agar 1.5 g., sodium chloride 0.72 g., sodium citrate 0.6 g., "Merthiolate" Lilly 0.01 g., trypan blue 0.01 g., distilled water to make 100 ml. Adjust pH to 6.7 with hydrochloric acid.

TUNA SERUM SAMPLES

The samples of tuna serum were obtained for his study by the biologists of the Bureau of Commercial Fisheries Biological Laboratory, Honolulu, Hawaii.

Table 1 gives a list of these samples. Since we have found little evidence for individual differences, information about the individual samples is not included. Information on place and date of capture, sex, and size are on file in the Bureau of Commerical Fisheries Biological Laboratory, Seattle, Wash.

TABLE 1.—*Samples of sera from adult tuna*

Species		Number of individual samples	Vessel	Year collected
Common name	Scientific name			
Albacore	*Thunnus alalunga*	11	*John R. Manning*	1957
Yellowfin	*Thunnus albacares*	8	*Charles H. Gilbert*	1957
		1	*Charles H. Gilbert*	1959
Bigeye	*Thunnus obesus*	8	*Charles H. Gilbert*	1958
		2	*Hugh M. Smith*	1959
kipjack	*Katsuwonus pelamis*	16	*Charles H. Gilbert*	1957
		19	*John R. Manning*	1957
Little tunny	*Euthynnus yaito*	2	*Charles H. Gilbert*	1957
		2	*John R. Manning*	1957
Dogtooth tuna	*Gymnosarda nuda*	2	*Charles H. Gilbert*	1957

TABLE 2.—*The distinction of species of adult tuna by means of double diffusion precipitation analysis of their sera with antisera prepared in rabbits*

Antiserum	Serum (tuna species)	Number of precipitation lines	Number of distinctive lines
Antialbacore	Albacore	7	----------
	Yellowfin	4	3
	Bigeye	5	2
	Skipjack	4	3
	Euthynnus	3	4
	Dogtooth	2	5
Antibigeye	Bigeye	11	----------
	Albacore	8	3
	Yellowfin	8	3
	Skipjack	5	6
	Euthynnus	5	6
	Dogtooth	3	8
Antiyellowfin	Yellowfin	9	----------
	Albacore	8	1
	Bigeye	8	1
	Skipjack	5	4
	Euthynnus	5	4
	Dogtooth	3	6
Antiskipjack	Skipjack	3	----------
	Albacore	2	1
	Yellowfin	2	1
	Bigeye	2	1
	Euthynnus	2	1
	Dogtooth	1	2
Anti-*Euthynnus*	Euthynnus	6	----------
	Albacore	5	1
	Yellowfin	5	1
	Bigeye	5	1
	Skipjack	5	1
	Dogtooth	5	1
Antidogtooth	Dogtooth	11	----------
	Albacore	4	7
	Yellowfin	4	7
	Bigeye	6	5
	Skipjack	4	7
	Euthynnus	4	7

Samples were taken by cutting the isthmus of tuna, collecting the spurting blood in bottles or bowls, allowing it to clot for 1 to 2 hours at air temperature and up to 24 hours under refrigeration. The serum was decanted from the clotted blood and clarified by centrifugation. Serum samples were then frozen and stored at −15° C. to −30° C. At our laboratory, samples being used were separated into small aliquots to avoid repeated thawing and freezing. Most samples were in excellent condition when received and have remained stable under frozen storage.

RESULTS

The results obtained with the most discriminating sera among those we have prepared are summarized in table 2. For example, when testing our most discriminating antialbacore serum, we find that there are seven distinguishable precipitation lines with albacore serum, four of which cross-react with yellowfin serum, five with bigeye serum, four with skipjack serum, three with *Euthynnus* serum and two with dogtooth serum. Thus, with this serum, the number of lines (antigens) which distinguish albacore from the other species are as follows: Three with yellowfin, two with bigeye, three with skipjack, four with *Euthynnus* and five with dogtooth. Illustrations of tests with antidogtooth and antibigeye sera are presented in figures 1 and 2.

Considerable variability exists among the discriminatory abilities of the various antisera, even when we use the best bleedings. (There is, of course, considerably more variability among the antisera in discriminatory ability when one considers the results obtained with some of the poorer ones.) We have antialbacore, antibigeye, and antidogtooth antisera which possess considerable discriminatory power. On the other hand, the discriminatory qualities of our best antiyellowfin, and antiskipjack and anti-*Euthynnus* antisera are not great. This points up the fact that there is considerable variability between individual rabbit sera, so that one may need to immunize 6 to 20 rabbits in order to produce an antiserum of

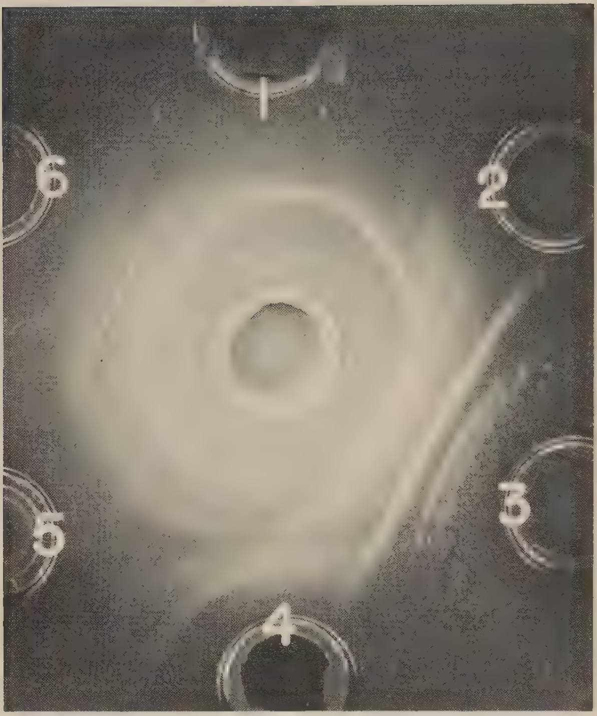

FIGURE 1.—The distinction of dogtooth tuna serum from that of other species. The peripheral wells contain sera of the following species: 1. *Euthynnus*. 2. Skipjack. 3. Dogtooth. 4. Yellowfin. 5. Albacore. 6. Bigeye. Antidogtooth-tuna-serum rabbit serum in center well. The random dots around dogtooth well are due to crystallization of material, which becomes insoluble on dilution, and have no effect on the immunological reaction.

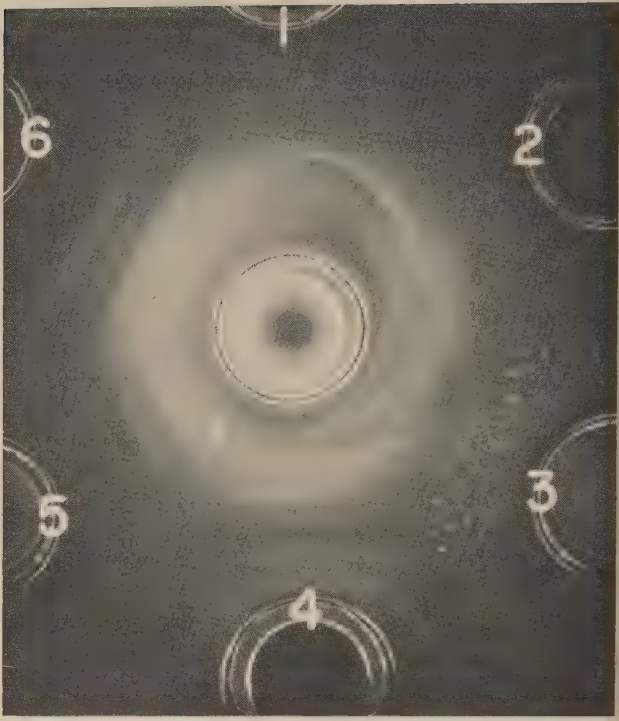

FIGURE 2.—Distinction of bigeye tuna serum from that of other species. The peripheral wells contain sera of the following species: 1. *Euthynnus*. 2. Skipjack. 3. Dogtooth. 4. Yellowfin. 5. Albacore. 6. Bigeye. Antibigeye-tuna-serum rabbit serum in center well.

the specificity necessary to make a particular distinction. We have noted this in some of our other work (Ridgway, Klontz, and Matsumoto, 1961), and this variability among the responses of several rabbits to the same antigenic stimulus has been pointed out by other immunologists.

That tuna species can be distinguished by the antigenic constitution of their sera, as summarized in table 2, has been confirmed by several replications. In the case of the albacore, yellowfin, and bigeye, distinctions were also made by absorption experiments. These absorptions were carried out both by the specific inhibition or intragel absorption method of Bjorklund (1952), which involves incorporating the absorbing tuna serum in the agar medium at a concentration of 20 percent; and by placing the absorbing serum in the center well for an interval of 10 to 20 minutes before adding the antiserum. All absorption experiments were carried out using the micromethod of agar diffusion (Ridgway, Klontz, and Matsumoto, 1961). In this method, 2 ml. of hot agar medium is pipetted on the unfrosted portion of a 25×75 mm. microscope slide which has been cleaned with alcohol. The antigen and antiserum wells are cut out of the agar using stainless steel punches of appropriate diameter. In these experiments summarized in table 3, 10 to 20 microliters of tuna sera were placed in the respective wells, the absorbing serum was placed in the central antiserum well also. After a short interval, 20 microliters of antiserum were placed in the center well and diffusion allowed to proceed for 4 hours at 37° C. and overnight in the refrigerator. It is evident from the results presented in table 3 that the closely related species bigeye, yellowfin, and albacore do possess species-specific antigenic factors as part of the constitution of their serum proteins, and that these factors can be detected with immune rabbit sera.

ABLE 3.—*Distinctive reactions of sera of species of adult tuna after removal of cross-reactive antibodies by absorption*

Antiserum	Absorbing serum	Test serum	Reaction (number of precipitation lines)
ntialbacore	Bigeye	Albacore	1
Do	do	Yellowfin	1
Do	do	Bigeye	0
Do	Yellowfin	Albacore	1
Do	do	Yellowfin	0
Do	do	Bigeye	0
ntiyellowfin	Albacore	Yellowfin	1
Do	do	Albacore	0
Do	do	Bigeye	1
Do	Bigeye	Yellowfin	2
Do	do	Albacore	1
Do	do	Bigeye	0
ntibigeye	Albacore	Bigeye	2
Do	do	Albacore	0
Do	do	Yellowfin	1
Do	Yellowfin	Bigeye	2
Do	do	Albacore	1
Do	do	Yellowfin	0

SOLUBLE TISSUE ANTIGEN STUDIES

Encouraged by the results obtained from our tudies of serum antigens we undertook some reliminary studies on the soluble antigens of uscle tissue. We felt that such antigens would e more useful for the identification of larval orms since muscle obviously makes up a larger ortion of the animal than does blood serum.

In order to adapt the double diffusion precipitin nalysis method to the detection and study of oluble tissue antigens of tuna flesh, and character- tic differences in them between species, several roblems had to be investigated first. These roblems included the development of methods r extraction of soluble antigens from tuna muscle ssue, stabilization of these extracts, and the roduction of potent and specific antisera.

The results of these studies can be summarized s follows: Extraction of muscle tissue with eutral physiological saline resulted in quite dilute nd unstable solutions from which most of the issolved protein precipitated spontaneously, even n overnight storage at 0° C. to 4° C. The use f alkaline saline solutions (pH 10) increased the fficiency of extraction and the stability of the olutions. From the standpoint of efficiency of xtraction and stability of the resulting solution, owever, the best extracting medium was found be 50 ml. glycerol, 1 g. NaCl, and water to ake 100 ml. The spontaneous precipitation hich occurred in muscle tissue extracts was creased by increasing temperatures or by freez- g and thawing. It was not significantly inhib- ed by heavy metal ions indicating that it may be due to causes other than the actions of proteolytic enzymes.

Three methods for the production of antisera were tried; intraperitoneal injection of several doses of untreated extract, intramuscular injection of alum precipitated extract, and the incorporation of the extract in Freund's adjuvant for an initial subcutaneous stimulation, followed by several intraperitoneal injections of the untreated extract after 2 to 3 weeks. The last method gave the most potent antisera.

Spontaneous precipitation of the extracts occurred during the diffusion tests which complicated their interpretation. Nevertheless we did find that skipjack differed from yellowfin, albacore, and bigeye by at least one tissue antigen detectable when the tests were run at 4° C. The soluble tissue antigens of yellowfin, albacore, and bigeye were not distinguishable using the antisera and methods we developed, but they did possess a character missing from the skipjack extracts.

The results of our preliminary studies also indicated that the soluble proteins of fish muscle tissue are antigenically quite distinct from the serum proteins of the same species. The few weak reactions obtained on testing tissue extracts with antiserum sera may be attributable to the presence of small amounts of blood and lymph in the tissues. In addition, the degree of cross-reactivity among taxonomic groupings of fish is apparently greater in the case of soluble muscle proteins than in the case of serum proteins. These findings may be of interest from the standpoints of ontogeny and evolution, but they increase the difficulties involved in the utilization of soluble tissue antigens for the distinction of species.

DISCUSSION

The demonstration of interspecific differences in serum protein antigens of tuna with only a small-scale study indicates that there are definite possibilities in the application of immunochemical methods to the problem of identifying the species of larval forms of tuna. This is, of course, dependent on the development of species specificity in antigenic constitution early in embryological development. There are ultramicro precipitin methods available for the study of soluble antigens, for example the double diffusion method can be carried out on cellulose acetate films as reported by Consden and Kohn (1959), with as little as

0.001 ml. of serum. With potent and specific antisera the usual ring test can detect even smaller amounts of antigen. A larger scale program utilizing a great many more rabbits could probably develop such potent and specific antisera.

Nevertheless, it seemed more reasonable to study the soluble antigens of muscle tissue since muscle makes up a much larger portion of the animal than does serum. However, our finding that the soluble antigens of tissue appear to be less distinct than those of serum, coupled with the technical problems involved in preventing spontaneous precipitation of tissue antigens, indicates that soluble tissue antigens may not be the best material for use in the distinction of tuna species. More study of these antigens is warranted, especially the investigation of other methods of immunization in order to produce more discriminating antisera, and the examination of methods for extracting only the more stable antigens.

An even more promising approach is the use of insoluble cellular antigens. There is evidence from the studies of Cushing (1956) and Suzuki, Shimizu, and Morio (1958) that interspecific differences in the red cell antigens of tuna exist. The production of species-specific hemagglutinating antisera is also readily accomplished because of the relative ease of absorption with red cells. On the other hand, removal of cross-reacting precipitins by absorption is difficult to accomplish satisfactorily. The presence of species-specific red cell antigens in other tissues of the larval tuna would, of course, be required for the application of this method. In human beings and certain other mammals red cell antigens have been demonstrated to be present in other tissues. The techniques available for testing for these antigens in tissues include the mixed agglutination method which has been used to demonstrate the presence of A and B antigens in human epithelial cells by Coombs, Bedford, and Rouillard (1956) and the fluorescent antibody techniques of Coons (1954) which are so sensitive that the presence of antigens on individual cells is demonstrable.

Of course, suitable preservation methods will have to be developed for the maintenance of the antigens of larvae from the time the larvae are collected until they can be sorted from the plankton and tested.

Undoubtedly, the way is open for greater application of the ultrasensitive methods of immunochemistry and blood-group serology to problems of fishery biology. The important thing to be recognized is that these methods are not in the nature of "magic wands", but are developed and applied through knowledge and painstaking experimentation.

SUMMARY

Through the application of the Ouchterlony method of diffusion precipitin analysis, with rabbit immune sera, the presence of species-specific differences in serum antigens of adult tuna was demonstrated. The existence of these differences was confirmed by absorption methods.

In studies on soluble antigens of the muscle tissue of tuna, evidence was obtained for distinguishing skipjack from albacore, yellowfin, and bigeye tuna.

No characteristic differences in their soluble tissue antigens were found which allowed the mutual distinction of the latter three species. In the study of soluble tissue antigens, technical problems involving extraction media, stability of extracts, and production of potent antisera were encountered and preliminary methods for their solution developed.

The course which further developments in these and allied fields might take resulting in possible distinction of larval forms was discussed.

ACKNOWLEDGMENTS

Charles Matsumoto, Mary LaRocque Ullman, and George W. Klontz assisted in conducting the experiments described. Biologists of the Bureau of Commercial Fisheries Biological Laboratory, Honolulu, Hawaii, collected the tuna blood samples under difficult conditions.

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THEORY ON DEVELOPMENT OF MOUNDS NEAR RED BLUFF, CALIF.

y HAROLD A. GANGMARK, *Fishery Biologist*, and F. BRUCE SANFORD, *Chemist-in-Charge*, BRANCH OF REPORTS,
BUREAU OF COMMERCIAL FISHERIES

ABSTRACT

Photographs are presented showing mounds in varous stages of development in the flood zone of the acramento River near Red Bluff, Calif., and the terrain on which the mounds are located. A theory is presented to explain how the mounds were formed.

Rounded mounds of earth, such as in figure 1, re found in many parts of North, Central, and outh America and possibly in other parts of the orld. The striking appearance and puzzling eatures exhibited by the mounds have long nade them objects of scientific curiosity. Of the nany theories proposed during the last 100 years) account for their formation, none is universally ccepted. Literature on the subject is too exensive to be cited here, but Scheffer (1947, 1958) nd McGinnies (1960) list sufficient references) give a good review.

Incidental to an ecological investigation of reams as nursery areas for the production of hinook salmon (*Oncorhynchus tshawytscha*), a ection of the Sacramento River near Red Bluff, alif. (fig. 2) was studied, where mounds are in any stages of growth. When one looks at these ounds, he finds that in a restricted area, they onstitute a family. They tend toward an ellipidal form, and their long axes are parallel to e another. If one cuts through a mound, he nds that it is composed largely of silt with some nd, stones, and decayed matter (fig. 3). The bstratum of the mound is made up of gravel d coarse sand.

Our curiosity having been aroused by these servations, we developed a theory to explain w the mounds were formed. Although the subject of mounds is not directly a part of fishery studies, the agents that we think lead to the formation of mounds—namely, flooding of the stream and erosion of soil materials—also kill salmon by scouring the stream gravel or by depositing silt in the streambed. This action destroys incubating spawn by removing gravel and washing out the eggs and by depositing silt and subsequently smothering the eggs. Similarly, larvae and other aquatic forms that the salmon fry eat are either washed out or the habitat of these forms is destroyed by deposition of silt, and the food supply for the young salmon is greatly diminished.

Mounds thus serve as tangible evidence of stream phenomena that are of vital concern to the fishery biologist. We believe that an understanding of the agents involved in the formation of mounds will contribute to a better understanding of the factors that determine whether the streambed will be a productive habitat for salmon when spawning.

How dynamic conditions during flood seasons lead to the formation of mounds can best be seen by photographs. The purpose of this report therefore is to present pictures of mounds in various stages of formation and then to give a theory summarizing the photographic observations.

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ote.—Approved for publication June 21, 1961.

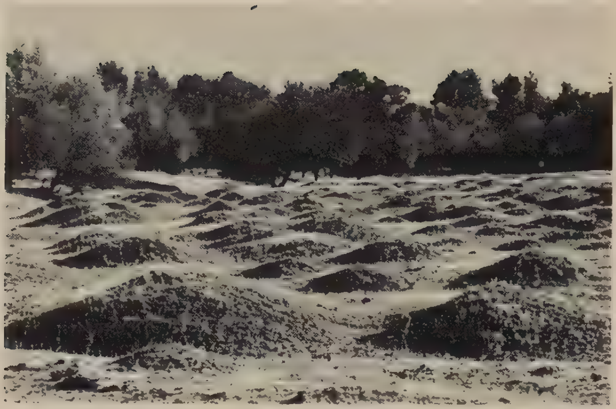


Figure 1.—Mounds near Red Bluff, Calif.

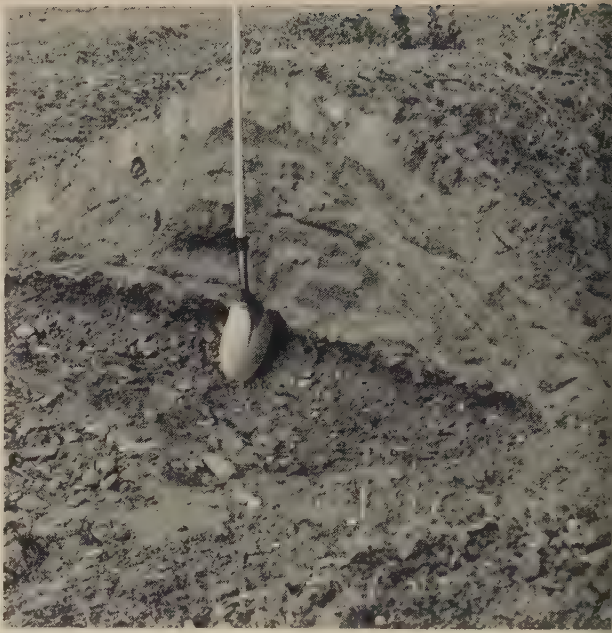


Figure 3.—A cross section cut through a typical mound shows a deposition of silt, some decayed organic matter, sand, and an occasional stone on a substratum of gravel and coarse sand. This particular ellipsoidically shaped mound was 3 feet high, 13 feet wide, and 20 feet long.

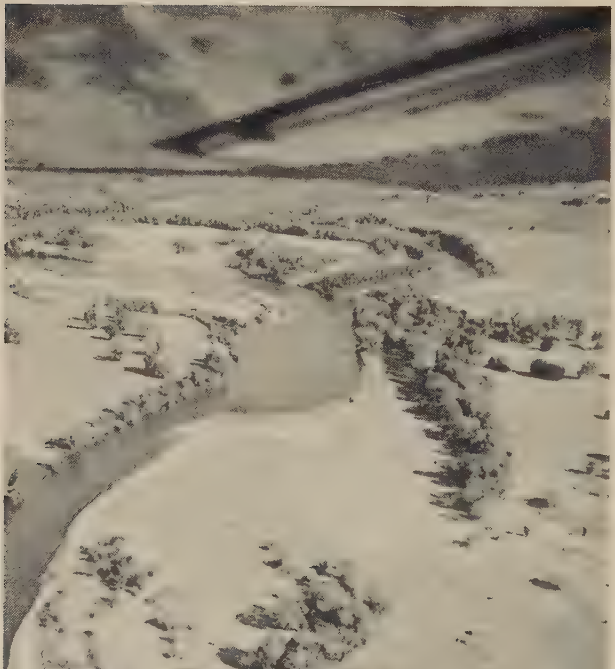


Figure 2.—The mounds shown in figure 1 were near the middle of the extreme right area.

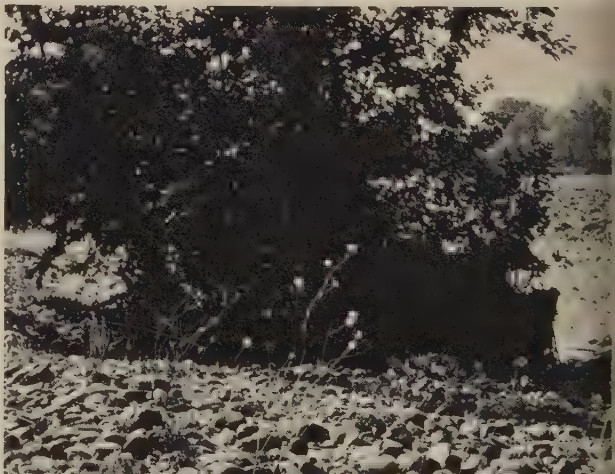
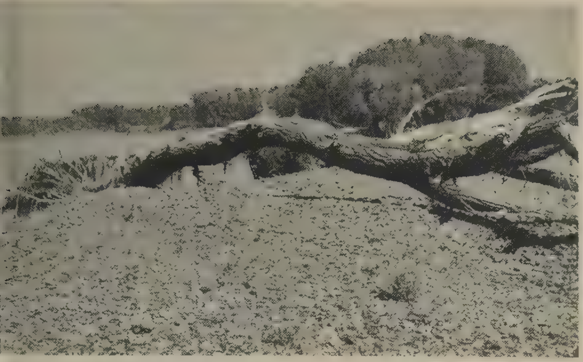
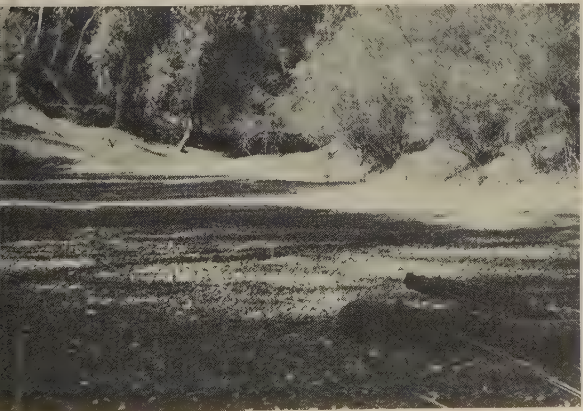


Figure 4.—During flood season, water moved down the river channel with tremendous force, carrying gravel, boulders, and debris and depositing these materials wherever the current slowed. The brush piled against this tree indicates how the streambed is changing continuously during a flood.



GURE 5.—Gravel accumulated by the force of flooding waters elevated the streambed. Note how the roots of this large tree are partially hidden by the gravel bar in the foreground. Bars such as this one are several feet above the normal height of the river seen at the base of the trees in the far distance. The large tree left here when the river receded indicates how the river valley changes during a flood. It shows how both the streambed and the direction of flow of water must be continuously varying.

GURE 6.—With the increase in height of the bed, the river changed its course because a new channel was readily eroded through the comparatively light soil of the adjacent area.



URE 7.—In time, the river became completely diverted rom its old channel, demonstrating the dynamic and ontinuously changing conditions during the flood season.

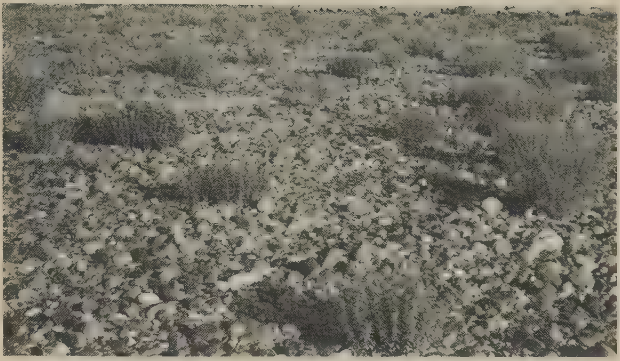


Figure 8.—The elevated streambed was inundated during floods but was dry during a sufficiently long period of the year to allow plants such as mountain monardella (*Monardella odoratissima* Benth) and brickellbush (*Brickellia californica*) to become established and grow.

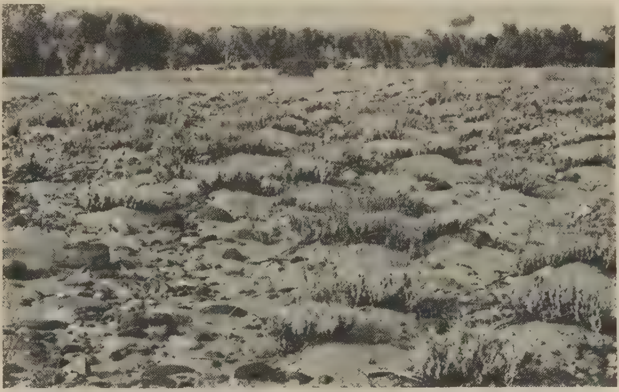


Figure 9.—Almost any plant in the area, such as wild buckwheat (*Eriogonum wrightii*), shown here, was capable of forming incipient mounds.

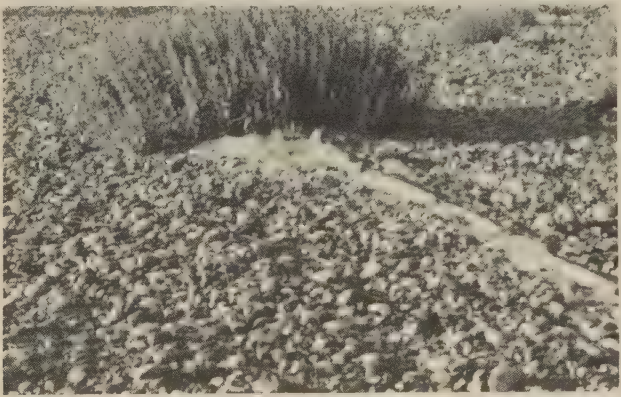


Figure 10.—During flood seasons, the plant was an obstacle to the flow of the soil-bearing stream, causing the rate of flow to be reduced sufficiently so that soil was deposited immediately downstream from the plant. Some of the deposits measured as long as 65 feet.

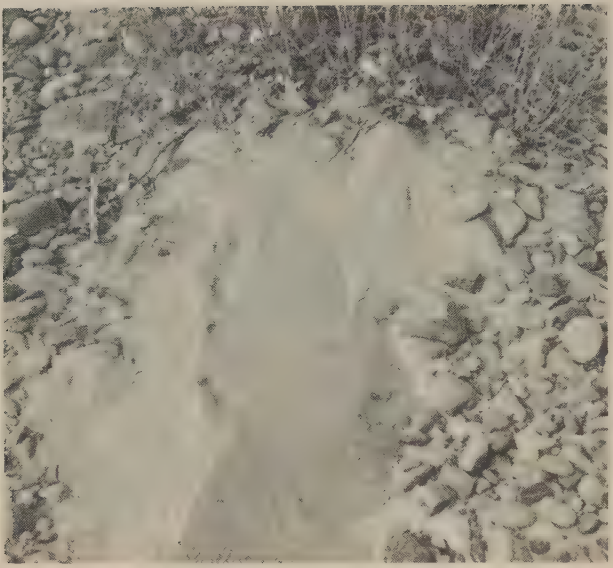


FIGURE 11.—As the incipient mound grew, the stream contoured it into teardrop shape.

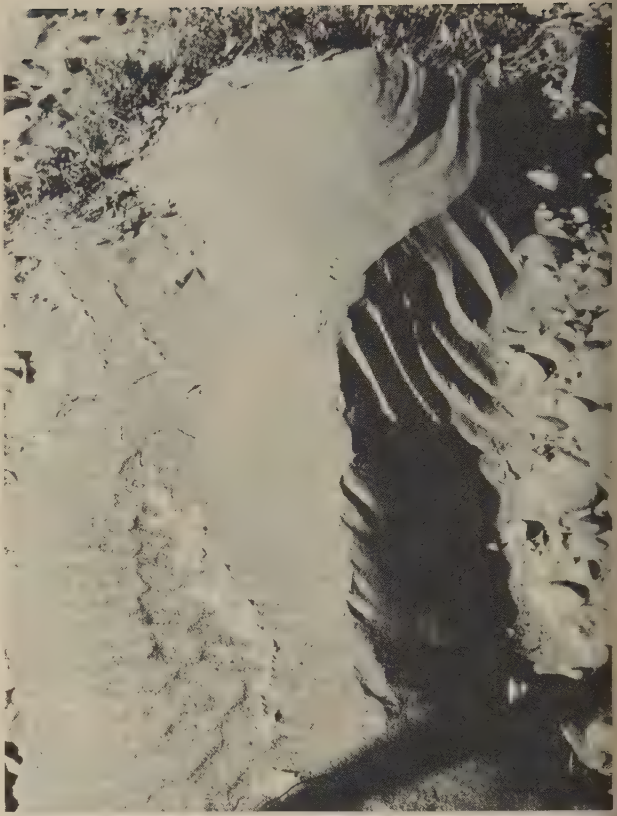


FIGURE 13.—Growth of the mound changed the local direction of the stream. Note how the head of the deposit was contoured into an ellipsoidal form. The head of the mound was composed of finer material than the tail, indicating that the flow was less swift close to the plant.

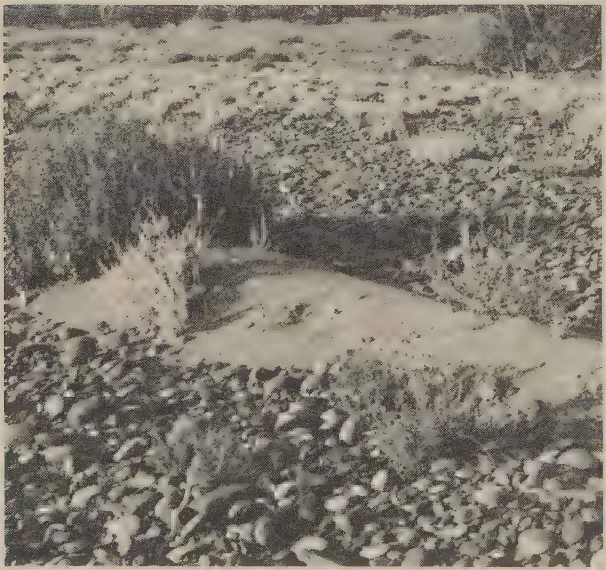


FIGURE 12.—Continued deposition resulted in a shallow, elongated accumulation of silt, sand, and pebbles.

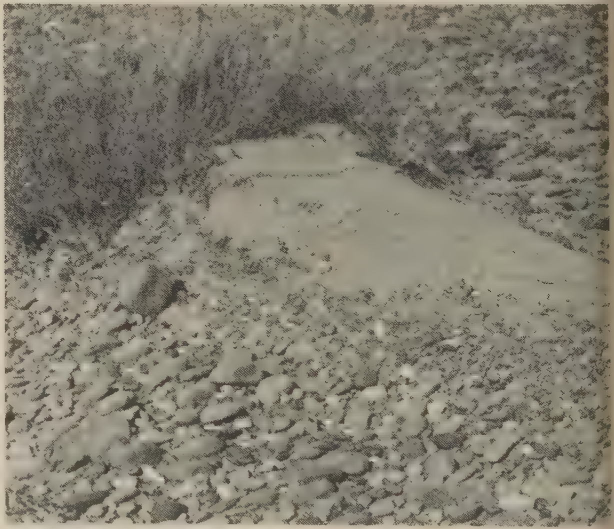
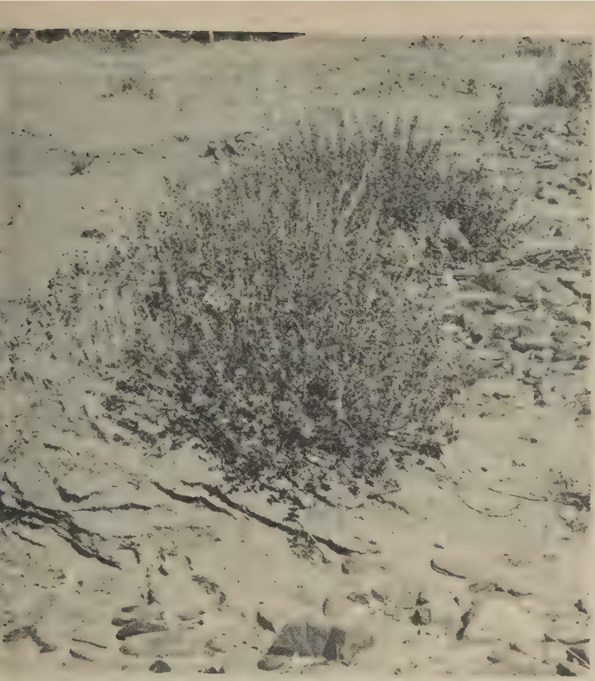
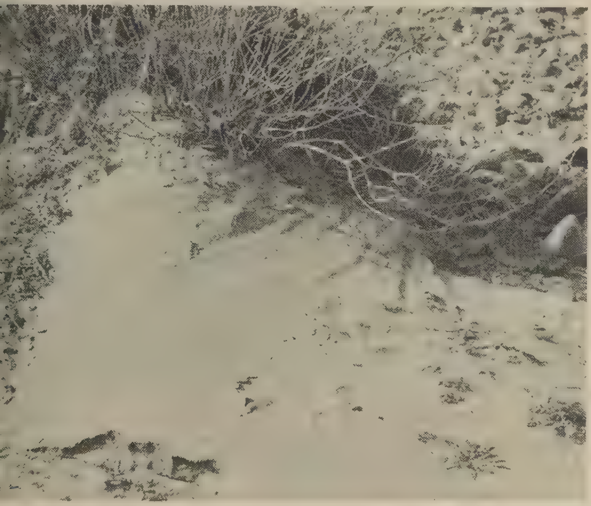


FIGURE 14.—The precise shape of the deposit was determined by the relative rates of deposition and erosion as the stream continuously changed direction of flow.



GURE 15.—If the velocity of the stream became too great, the mound was eroded badly, especially if large changes took place in the direction of the stream as might occur when the stream was rising or falling in a somewhat sloping area.



GURE 16.—The changes in the direction of flow of the tream tended mostly to favor the deposition and erosion f the mound into ellipsoidal or hemispherical shape. Note the circular contours on this developing mound. Note also how the growth of plants is helping to stabilize he mound.

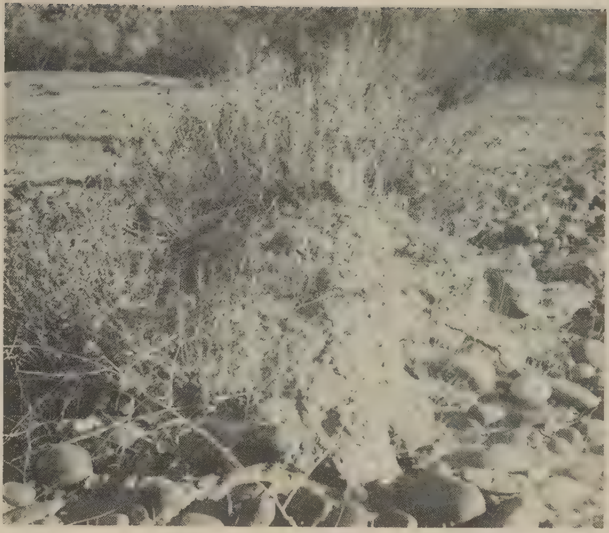


FIGURE 17.—Large changes in the direction of the stream, accompanied by high rate of flow, produced drastic changes in the shape of the mound, the change tending, however, to favor the ellipsoidal or hemispherical form.

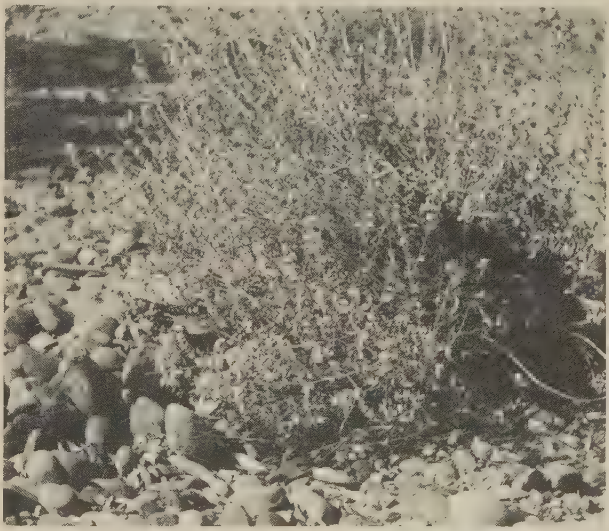


FIGURE 18.—If the stream became too rapid, the entire mound was eroded leaving the roots of the original mound-forming plant exposed.

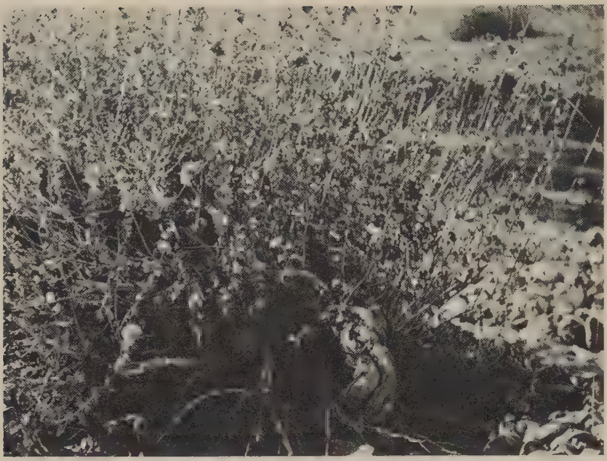


FIGURE 19.—Only plants with exceptionally strong roots could withstand the force of the river under high velocities and changing directions of flow, and only plants such as brickellbush, which grows even when soil accumulates around it, could form mounds of appreciable size.

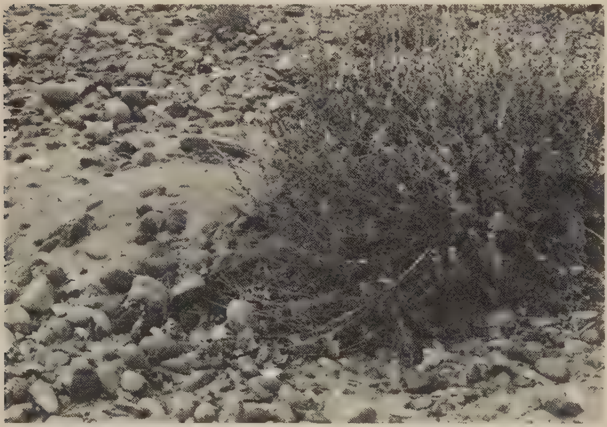


FIGURE 20.—A surviving plant (see figs. 18 and 19) started the formation of a new mound. This photograph was taken 1 year later.

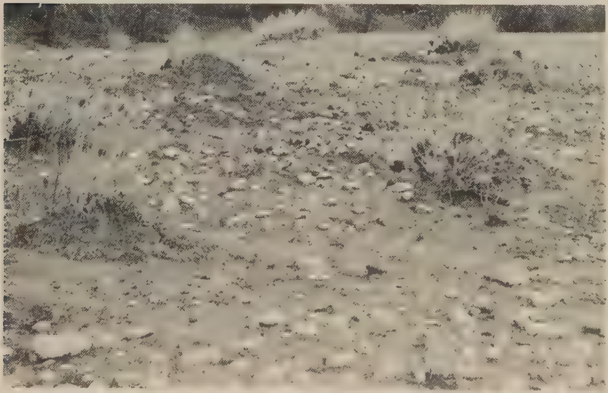


FIGURE 21.—Mounds were haphazardly distributed, depending upon where the plants happened to grow.

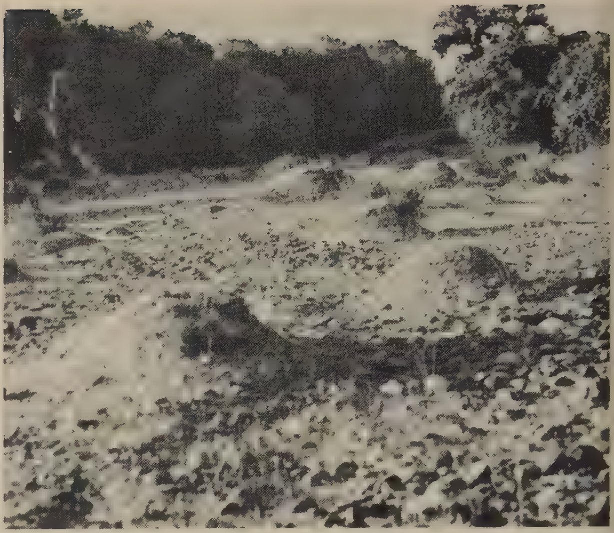


FIGURE 22.—Under conditions of equilibrium, mounds attained a stable form and continued to increase in size.

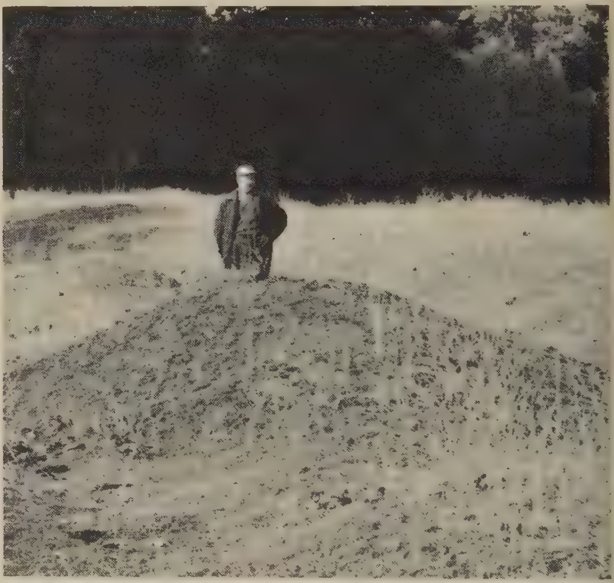


FIGURE 23.—Because of the shift in the course of the river, the environment changed, creating conditions adverse to the mound-forming plants and resulting in the death and disappearance of these plants on the mounds farthest from the stream.

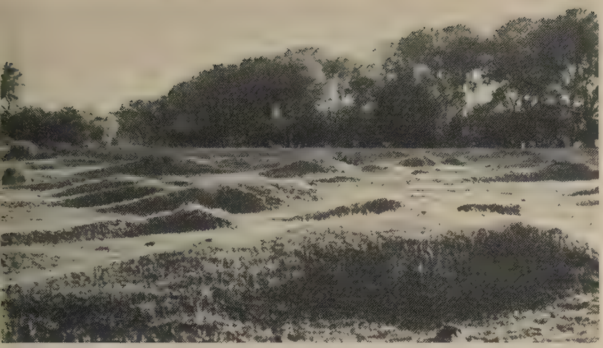


FIGURE 24.—The mounds were all oriented with the elongated axes in the direction of flow of the river. This photograph was taken at right angles to the flow and points in the direction that the river channel has shifted. Moving away from the camera toward the river, we find three zones of transition: first, no brickellbush (in the foreground); second, brickellbush struggling for existence (in the middle background); and finally closest to the river, healthy brickellbush (left background).

IGURE 25.—On the older mounds, all signs of the orginal mound-forming plants disappeared except possibly for the partially decayed roots (brickellbush in this case). Roots such as these extended down into the substratum at the upstream extremity of all mounds examined.

THEORY

1. During flood seasons such plants as mountain onardella and brickellbush, which grow on the ood plain between flood seasons, are obstacles o the flow of water. Because the rate of flow has een slowed, silt is deposited in an elongated attern immediately downstream from the plants. uring the period of early growth of the mound, the elongated deposit tends to be molded into a teardrop shape by the stream.

2. The head of the mound, being protected by the mound-forming plants, tends to be more permanent than is the tail. Any major changes in the direction of flow of the floodwater will tend to erode the tail faster than the head.

3. As the head of the mound grows in size, it produces local changes in the direction of flow of the floodwater in such a manner as to contour the mound into ellipsoidal form, with the hemispherical form being the limit toward which the contouring tends.

4. Owing to the mounds having been formed by deposition of silt, sand, and stones from moving floodwater, the long axes of the mounds are all parallel to one another and to the direction of flow of the floodwater.

5. Any plant growing on the flood plain can form an incipient mound, but only plants that have strong roots, that can withstand having their lower portion covered gradually by silt, and that have a long life span, such as brickellbush, will form large mounds.

6. Shifting of the streambed produces a change in environment that is unfavorable to the mound-forming plant, so it eventually dies and disappears. The mound now exhibits no surface evidence of this essential agent in its formation.

SUMMARY

Photographs taken on the flood plain of the Sacramento River near Red Bluff, Calif., are presented showing present-day development of mounds in all stages from incipient to mature. A theory is given summarizing the photographic observations.

The essential feature of the theory is that the mounds are formed immediately downstream from certain plants such as mountain monardella (*Monardella odoratissima* Benth) and brickellbush (*Brickellia californica*) during flood seasons, owing to the resistance offered by the plant to the flow of water and consequent slowing of the stream and deposition of suspended soil. The ellipsoidal shape of the mounds is explained as the product of two opposing tendencies: Deposition and erosion. The deposition is elongated downstream from the plant, whereas the erosion tends to shape the deposit into hemispherical form—that being the most stable to changing direction of flow.

The parallel orientation of the long axes of the mounds is explained by all of the mounds being formed by deposition from the same stream.

ACKNOWLEDGMENTS

T. C. Fuller and S. T. Ancell of the California Department of Agriculture identified the plants mentioned in the report. John Riggs of the California Department of Fish and Game took the photograph in figure 2. Albert Redamonti gave permission to make the observations on his property.

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EFFECT OF FISHWAY SLOPE ON PERFORMANCE AND BIOCHEMISTRY OF SALMONIDS[1]

By GERALD B. COLLINS, CARL H. ELLING, JOSEPH R. GAULEY, AND CLARK S. THOMPSON, *Fishery Biologists*

BUREAU OF COMMERCIAL FISHERIES

ABSTRACT

The effect of fishway slope on the performance and iochemical state of salmonids was studied in two xperimental "endless" fishways with slopes of 1 on 8 nd 1 on 16. A locking device in each fishway permitted ecycling of fish so that pool-and-overfall fishways of ny height could be simulated. Ascents were generally onfined to a rise of 104 feet, but a number of fish were ermitted to ascend over several hundred feet and one sh was allowed to ascend over 6,000 feet. Principal pecies tested were chinook salmon (*Oncorhynchus shawytscha*), sockeye (Columbia River blueback) almon (*O. nerka*), and steelhead trout (*Salmo airdneri*).

Comparisons of individual passage times, patterns of movement, and biochemical phenomena associated with muscular activity showed no evidence of fatigue of the fish in either fishway when proper hydraulic conditions existed. Data indicated that ascent of a properly designed pool-and-overfall fishway is only a moderate exercise for salmonids and that the rate of ascent will not decline in the upper end of a long fishway. Hydraulic conditions were shown to control rate of ascent and pattern of movement through fishways. Differences in rate of movement and in blood lactate levels were measured between species.

The effects of size, sex, maturity, and disease on performance and biochemical state of fish were also examined. Significant relationships were found only for length of male chinook and performance (larger fish were slower), and sex and blood lactate level for chinook (female chinook had higher blood lactate levels).

The slope of a pool-type fishway is a major actor in determining the cost of its construction. fishway that rises 1 foot for every 8 feet of ength (1-on-8 slope) needs to be only one-half s long as a fishway that rises 1 foot for every 6 feet of length (1-on-16 slope) to gain the same levation. On the Columbia River the present tandard slope for major fishways is 1 on 16, (e.g., onneville Dam, The Dalles Dam and Rocky each Dam). An earlier dam, Rock Island Dam, as built with fishways with a 1-on-10 slope, and he dam, McNary Dam. has fishways with a slope of 1 on 20. There are many dams yet to be built on the Columbia River and its tributaries, and significant reduction in fishway costs would be possible if satisfactory fishways could be designed with slopes steeper than the present 1 on 16.

To determine the feasibility of steeper fishway slopes the effect of fishway slope on the rate of passage of chinook salmon (*Oncorhynchus tshawytscha*), sockeye salmon (*O. nerka*), and steelhead trout (*Salmo gairdneri*) was studied at the research project at Bonneville Dam during 1956 and 1957. This was done by comparing the passage times of the salmonids through short experimental fishways with slopes of 1 on 8 and 1 on 16. Both fishways were of the pool-and-overfall type without submerged orifices, and both achieved a total gain in elevation of 6 feet. The results of these experi-

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NOTE.—Approved for publication Nov. 29, 1961.

[1] This study was financed by the U.S. Army Corps of Engineers as part of road program of fisheries-engineering research for the purpose of providing sign criteria for more economical and more efficient fish-passage facilities Corps' projects on the Columbia River.

ments (Gauley, 1960, p. 11) were quite favorable. For all three species of fish the rate of passage through a 1-on-8-slope fishway having 1-foot overfalls between pools was as fast or faster than the rate of passage through the conventional 1-on-16-slope fishway. This was true whether the tests were made with individual fish or with groups of fish. However, because the tests in 1956 and 1957 were made with only short segments of fishways, the question still remained whether the steeper slopes were suitable for longer fishways. The possibility that the steeper slope might dangerously fatigue fish in a long fishway had to be investigated.

A study of the effect of fishway slope on fish performance in long fishways was begun at the Fisheries-Engineering Research Laboratory during the 1958 season. Two specially designed "endless" fishways with slopes of 1 on 8 and 1 on 16 were utilized. These endless fishways were experimental pool-and-overfall fishways constructed so that each made a complete circuit, with the highest pool connected to the lowest pool by means of a lock. When a fish had ascended to the top of one of these fishways it was then rapidly locked to the lowest pool to ascend again. Fishways of any desired length could thus be simulated. Knowledge of the effect of fishway slope on fish passage was sought through a comparison of the performance and behavior of the fish in the two endless fishways and through a study of the related biochemical phenomena associated with fatigue.

DESCRIPTION AND OPERATION OF ENDLESS FISHWAYS

INITIAL DESIGN

Features of the 1-on-16 and 1-on-8-slope endless fishways and essential auxiliary channels and pools (entrance channel, collection pool, release compartment, introductory pool and exit by-pass) are shown in plan view in figure 1. An enlarged view of the 1-on-8-slope unit showing pool elevations in feet above mean sea level appears in figure 2. All subsequent reference to the various pools will be made by numbers indicating their surface elevation in feet above mean sea level. The same pool elevations apply to the 1-on-16-slope unit. Perspective views of the two fishways are presented in figures 3, 4, 5, and 6.

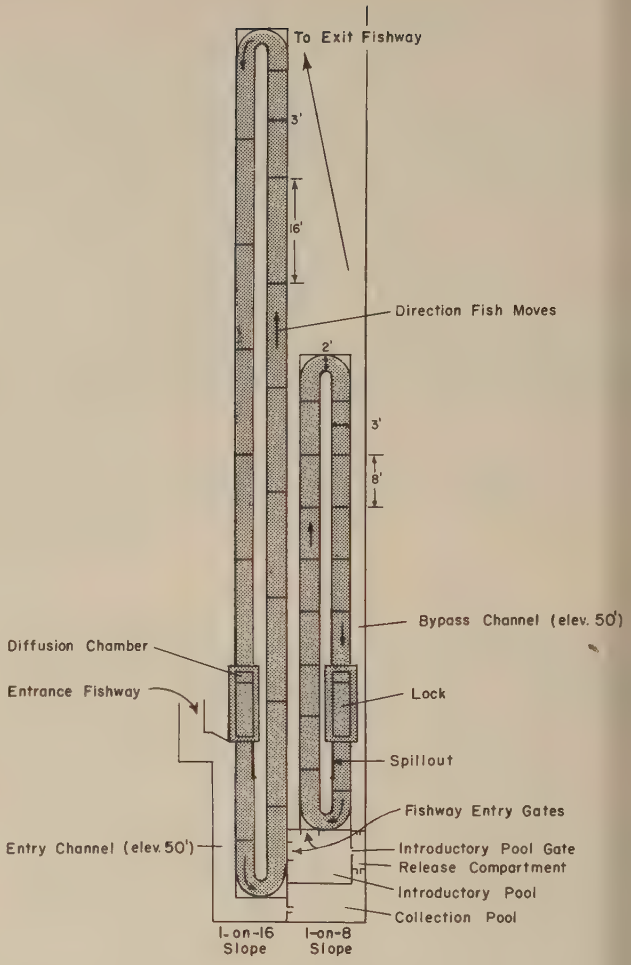
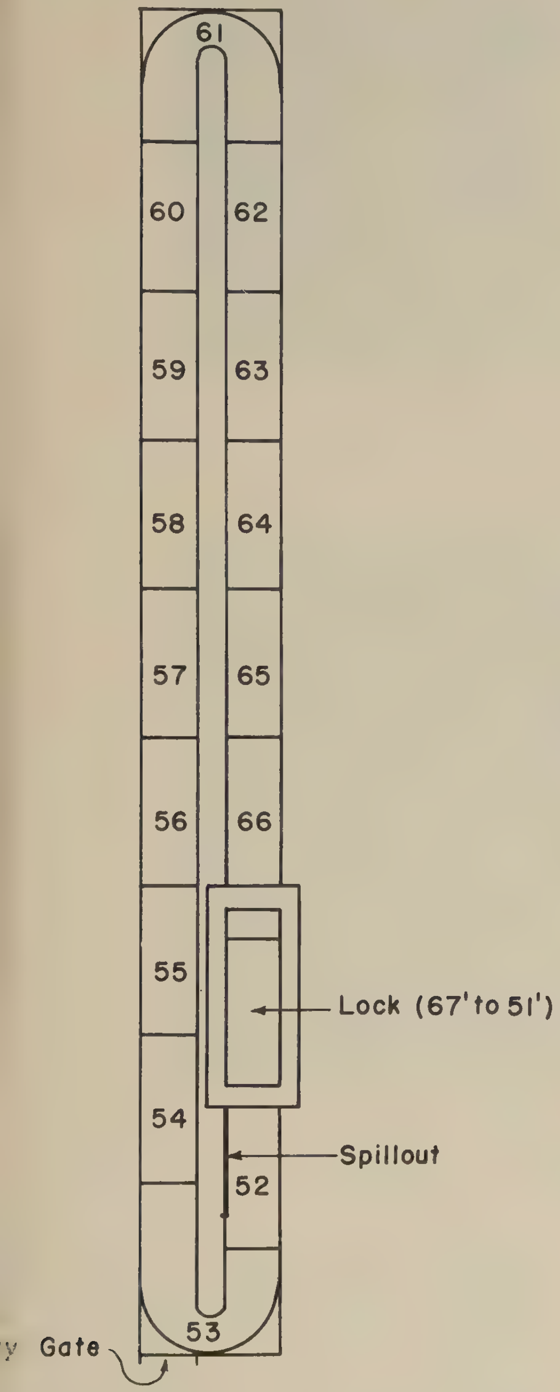


FIGURE 1.—Plan view of the 1-on-16-slope and 1-on-8-slope endless fishways with auxiliary approach channels and pools.

Each fishway was comprised of 16 pools including 2 turn pools and a locking pool. There was a 1-foot rise between pools and a total rise of 16 feet in the complete circuit. With the exception of the lock and turn pools, the average water depth in each pool was approximately 6.8 feet. Pools were 3 feet wide and either 8 or 16 feet long, depending on the slope of the respective fishway. A 3-foot freeboard prevailed throughout each fishway. Weir crests were 3 feet long and 2 inches wide and were painted white on the square crest to aid in the observation of fish. All other interior surfaces were painted camouflage brown. There were no orifices in the weirs, but a single, 2-inch drain hole was provided in the base of each weir to permit draining during unwatering. A steel plate covered each hole when the fishway was ative.

l principal structures were of wood with the ption of the exterior steel supports on the lock and certain gates in the two fishways. A cross-sectional view of a typical series of pools in the 1-on-8-slope unit, showing the box-type construction with level floor, is presented in figure 7.



RE 2.—Plan view of 1-on-8-slope fishway showing pool elevations in height above mean sea level.

Dimensions of the turn pools (53 and 61) were in keeping with the established slope in each fishway, i.e., the inside longitudinal footage totaled 8 feet in the 1-on-8-slope fishway and 16 feet in the 1-on-16-slope fishway. While pool depth was approximately 6.8 feet, passage area available to the fish was limited to the upper 2 feet of the pool by a horizontal grill. The corners of the pool were coved, and the pool width at the 90° point of the turn was reduced from 3 to 2 feet (figs. 1 and 8).

The lock pool (elevation 67′ to 51′) in each fishway was 8 feet long, 3 feet wide, and 23 feet deep when filled and 7 feet deep when drained. At the lower discharge level (elevation 51′), the lock functioned as a typical pool. A picketed barrier was installed on the crest of the downstream weir of the lock (elevation 50′) to prevent fish from drifting back into the drain area. Ideally, to be consistent with the slope design, the lock in the 1-on-16-slope fishway would have been 16 feet long. Since space limitations and structural considerations posed barriers to the construction of a 16-foot unit, the lock in the 1-on-16 fishway was built identical to that in the 1-on-8-slope unit.

To encourage the fish to pass from the lock pool after the water had been discharged from elevation 67′ to 51′, a horizontal grill was placed in the pool, limiting the depth available to fish to 2 feet. This alteration served to expedite the movement of fish from the lock into the next upstream pool (52).

Operational features of the endless fishway units may be conveniently described by visualizing the passage of a fish into and through the various sections of the laboratory and through an endless fishway. Steps involved in this passage are as follows:

(1) Fish were diverted from the Washington-shore fishway into the entrance fishway (fig. 1) without handling, a unique feature of the research. The fish then ascended the entrance fishway to the entry channel and moved on into the collection pool. This pool was 5 feet by 12 feet by 6 feet with the surface elevation at 50′.

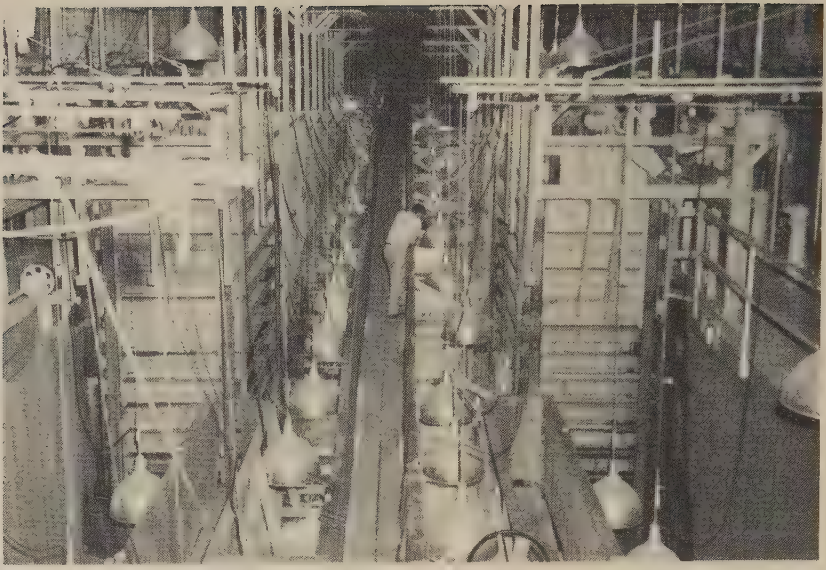


Figure 3.—Looking upstream at the 1-on-16 (left) and 1-on-8-slope (right) endless fishways. The locking units in each fishway appear in the left and right foreground.

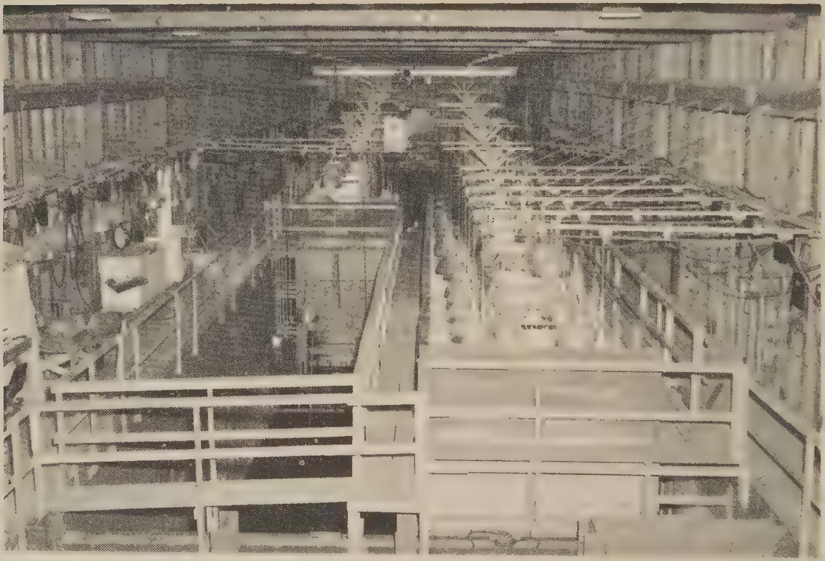


Figure 4.—View from the upper turn pool showing respective lengths of the 1-on-16 (right) and 1-on-8-slope (left) fishways. Each fishway rises 16 feet.

(2) From the collection pool a single fish was permitted to pass through an 8-inch-wide gate and enter the release compartment where it was diverted into the introductory pool through an adjoining gate. Water flow from the bypass channel provided the necessary attraction for the movement into the release compartment.

(3) As the fish entered the introductory poo
wooden drop gate was lowered at the junctur
the release compartment and the introduct
pool. This isolated the fish in a quiet pool, wh
was 6 feet wide, 9 feet long, and 2 feet deep. T
water level at this point remained at elevat
50′.

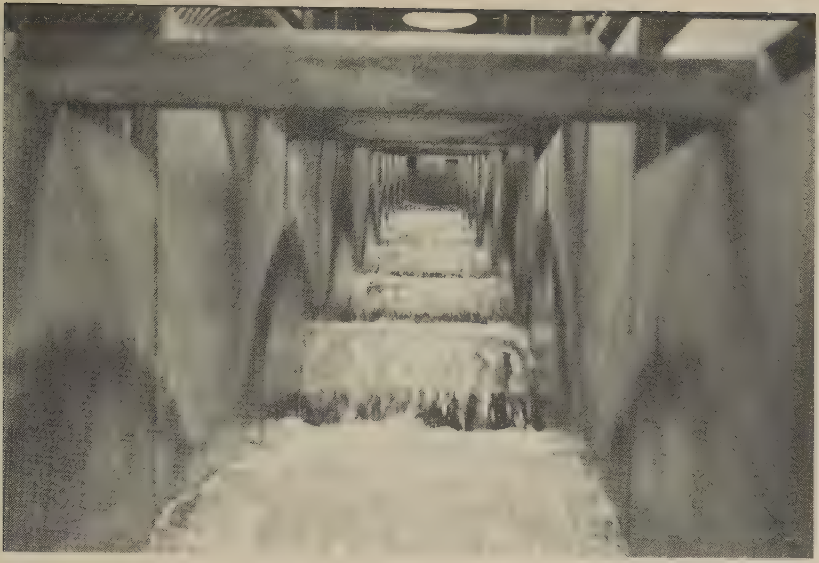


Figure 5.—Looking upstream from pool 53 in the 1-on-8-slope endless fishway.

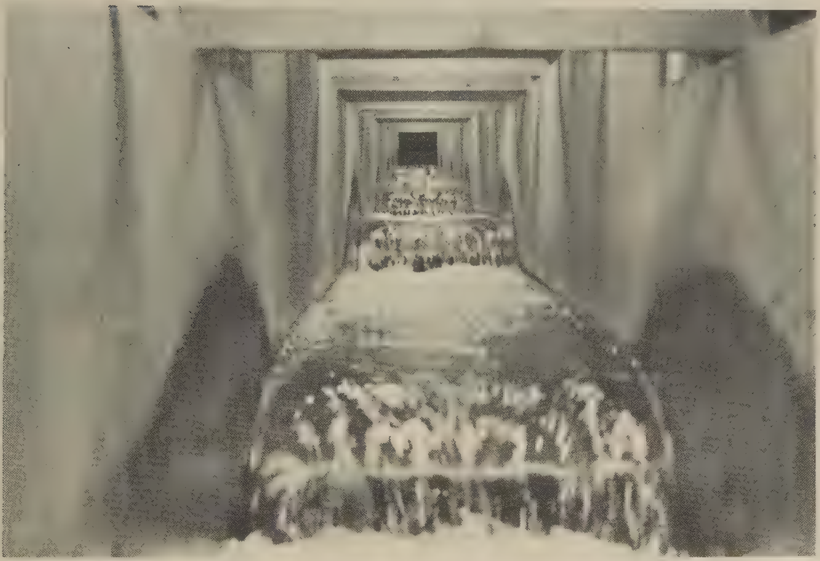


Figure 6.—The 1-on-16-slope endless fishway viewed from pool 53.

) Passage of the fish from the introductory to one of the endless fishway units was tated by raising a fishway entry gate joining 53 with the introductory pool. This per- ed the water in the fishway to spill into the ductory pool, filling it to approximately elevation 52.5′. At this level, excess water passed through a grill on the downstream rim of the introductory pool and spilled into the collection pool. The fish was now in a position to swim from the introductory pool (fig. 9) into the fishway.

(5) Immediately after the fish passed into pool

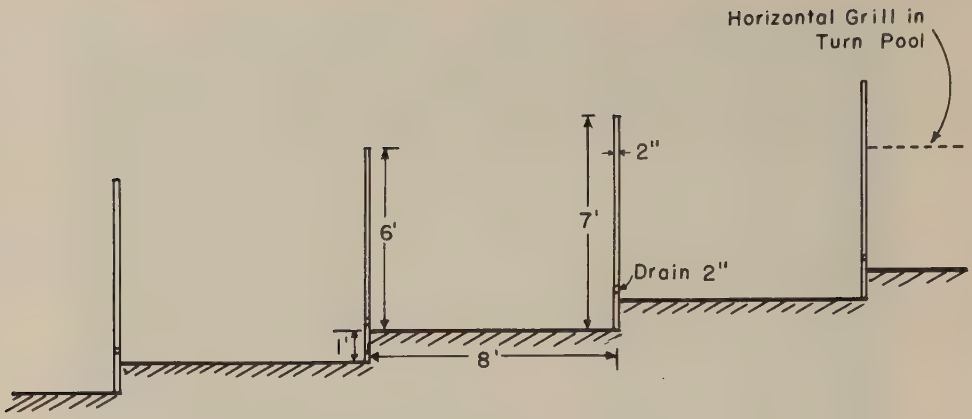


FIGURE 7.—Sectional view of 1-on-8-slope fishway. Note level floors.

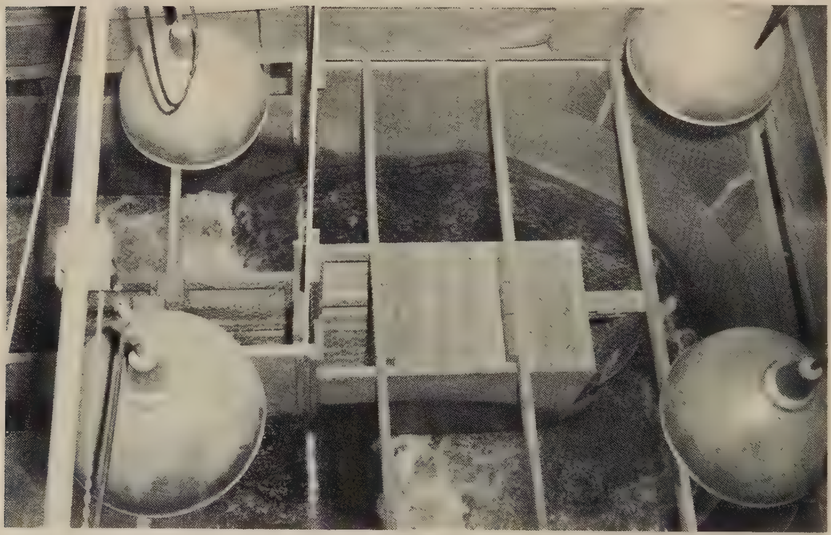


FIGURE 8.—Upper turn pool in the 1-on-8-slope fishway.

53, the fishway entry gate was dropped, isolating the fish in the now closed circuit of the endless fishway.

(6) From pool 53 (see fig. 2 for pool elevations) the fish ascended the straightaway section through pools 54–60 and then around the upper turn pool (61) and again up a straightaway section to pool 66. At this point the fish was ready to enter the lock (fig. 10). Dimensions of the diffusion chamber were 3 feet by 3 feet by 7 feet. A 16-inch pipe with grill openings on the under side entered the base of the chamber and provided a constant water supply for the fishway. Diffusion baffles were placed above the pipe and a finger gri submerged approximately 6 inches beneath t water surface, prevented the fish from soundi into the chamber as it passed from pool 66 in the lock.

(7) After the fish passed over the diffusi chamber grill, the drop gate (A, fig. 10) w lowered to separate the lock pool from the diffusi area. A motor-driven winch, connected to a ste cable (B, fig. 10), raised a steel flap gate at t base of the drain area directly beneath t diffusion chamber. This permitted drainage of t lock to elevation 51′. Discharge of lock water w

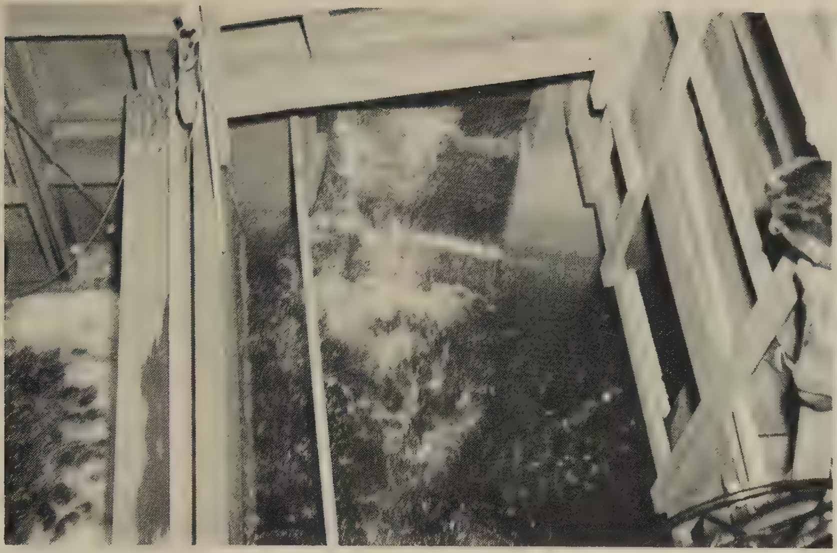


FIGURE 9.—Introductory pool with water level at elevation 52.5′. Entry gate to the 1-on-16 slope fishway is open (upper center) to permit entry of fish into pool 53.

ıally accomplished in about 30 to 40 seconds. ıre 11 shows drop gate (A) in down position, ting the diffusion chamber and the remainder e fishway from the lock which has been drawn ı.

) Figure 12 presents a view of the lock after ıarge of water from elevation 67′ to 51′. The cal gate (C) has been raised, and water from 52 may be seen spilling into the lock. (Pre- s to the opening of the pre-vertical gate (C), vater in the fishway spilled out a screened flow in pool 52.) The fish was now in position ove from the lock into pool 52.

) When the fish had passed through pool 52 the lower turn pool (53) the vertical gate (C) lowered and the lock drainage gate closed. readied the lock for filling as the fish began her circuit of the fishway. Filling the lock 13) required about 1 minute. As the water in the lock approached elevation 67′, the 16- supply valve was gradually closed. At this the drop gate (A) (figs. 10 and 11) was raised, the lock was now ready to receive the fish it once again ascended to this level.

LIGHTING AND HYDRAULICS

constant light supply approximating an aver- ntensity of 800 foot-candles at the water sur- prevailed during all experiments. This was provided by a battery of 1,000-watt fluorescent mercury-vapor lamps placed at 6-foot intervals throughout the course of each fishway. The distance from the lamp reflectors to the water surface was 6 feet.

Water supply for operation of the fishway units came from the forebay of Bonneville Dam, which fluctuated from elevation 82.5′ to 72.5′ during these experiments. This provided a minimum operating head of 5.5 feet (water level of lock and diffusion chamber when filled was approximately at elevation 67′). Water for the bypass channel (fig. 1) came from the Washington-shore fishway which was joined with the laboratory by an exit fishway.

Head on the weirs (measured 4 feet upstream of the weir crest) was controlled by adjusting the valve supplying water to the diffusion chamber. This head was set at 0.8 foot, the approximate upper limit at which a plunging flow (strong directional flow reaches bottom of pool) could be maintained under the prevailing nonorifice condition. Total discharge in each fishway was approximately 7.2 cubic feet per second (c.f.s.).

Flows into the lock pool were changed from the established plunging condition to a streaming motion (strong directional flow along surface of pool) by raising the lip of the lock spillout slightly above elevation 50′. This was done to increase the sur-

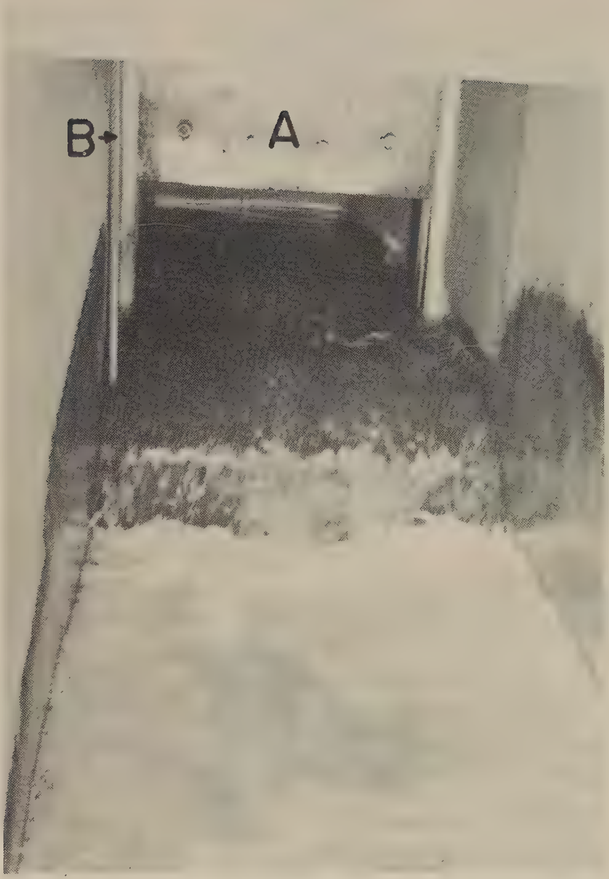


Figure 10.—Looking upstream from pool 66 over diffusion chamber and into lock. As fish enters lock, the drop gate (A) is lowered to isolate fish in lock. A motor-driven winch connected to the cable (B) raises a gate at base of lock, discharging water to elevation 51′.

face velocity and encourage the exit of fish from this pool.

SUBSEQUENT DESIGN MODIFICATIONS

During the 1958 experiments, several physical changes were incorporated in the fishways for the purpose of creating special hydraulic conditions designed to facilitate the passage of fish. The turn pools (53 and 61) in both fishways that had previously been grilled to limit fish passage to the 2-foot surface layer were further modified by installing a floor over the grill and placing 6-inch-high baffles on the floor at approximately 4-foot intervals across the width of the pool. These changes created a turbulent, rapidly flowing water pattern which served to prevent the fish from us
the turn pools as resting areas.

Following the above modifications, the 1-or
slope fishway was altered further by install
baffles on the weir crests (fig. 14). The three ty
of baffle placements were employed during t
conducted in September 1958.

A comparison of the various fishway conditi
applicable to the 1958 tests is given in table
Subsequent reference in the text will refer to th
conditions by number and slope.

PROCEDURE

The comparison of the two fishway slopes
to be based on an analysis of (a) the performa
of individual salmonids in the respective fishw
and (b) certain biochemical characteristics of
fish after exercise in the ascent of a fishway. F

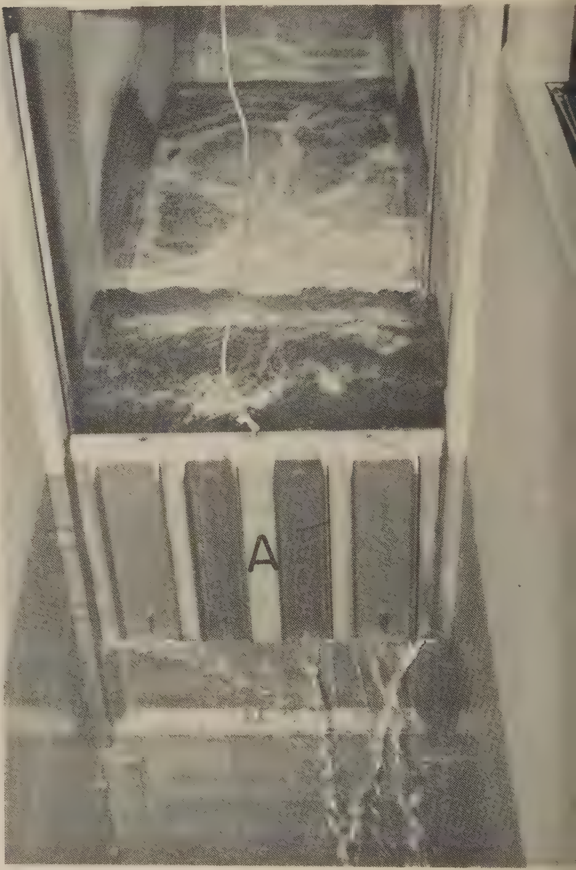
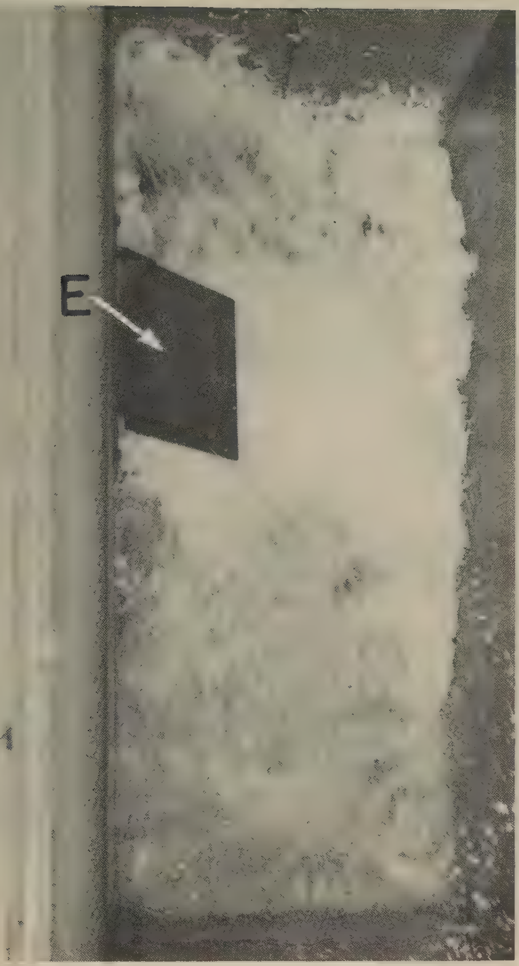


Figure 11.—Drop gate (A) in down position separa
diffusion chamber from lock (foreground). Wate
lock (foreground) has been discharged to elevation



E 12.—Looking down into lock. Vertical gate (C) been raised to permit exit of fish from lock into pool Water passes from lock through grill (D) and out n gate opening behind grill.

1.—*Physical features of 1-on-8 and 1-on-16 slope endless fishways* [1]

ishway		Weirs		Calculated flow	Turn pool conditions
ion	Slope	Length	Modifications		
		Inches		*c.f.s.*	
	1-on-8	36.0		7.2	With rest areas.
	1-on-16	36.0		7.2	Do.
	1-on-8	36.0		7.2	Turbulent.
	1-on-16	36.0		7.2	Do.
	1-on-8	17.0	Center notch—type A.	3.9	Do.
	1-on-8	26.5	In-line baffles—type B.	5.3	Do.
	1-on-8	26.5	Alternating baffles—type C.	5.3	Do.

vay pools were 8 and 16 feet long respectively, 3 feet wide and 6.8 feet
ead on weirs was 0.8 foot and height of overfall 1 foot.

formance was measured in terms of time and ability to ascend the two fishway and the biochemical characteristics measured were the levels of lactate of whole blood, inorganic phosphate of blood plasma, lactate of the muscle tissue, and inorganic phosphate of the muscle tissue.

FISH COLLECTION

Fish utilized for experimental purposes in the endless fishways were diverted from the Washington-shore fishway each day and allowed to ascend to the collection pool (fig. 1). The time required to collect a sufficient number of fish generally was not more than several hours. In the early part of the season, the collection period commenced at about 2:00 p.m. and by 4:00 p.m., 6 to 20 fish

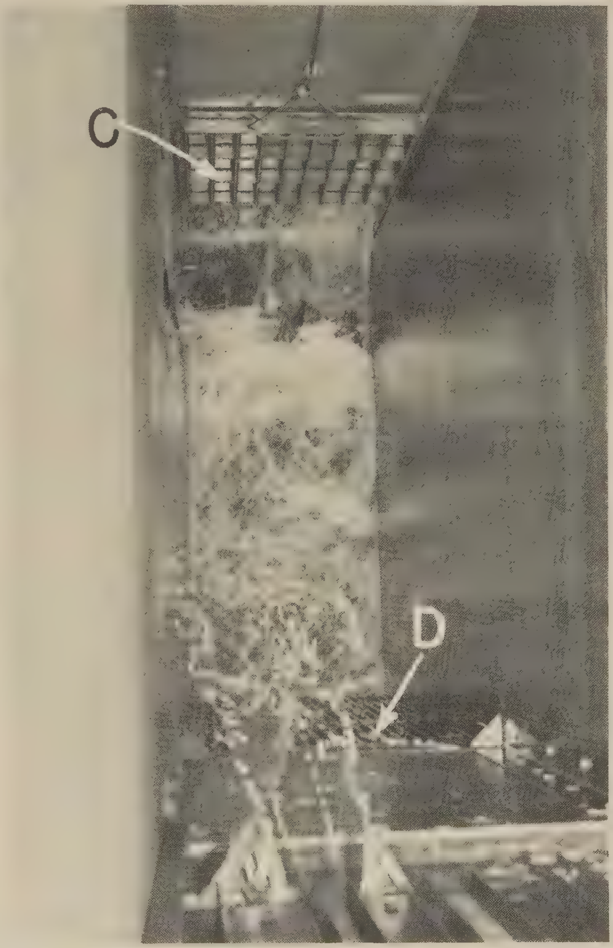


FIGURE 13.—Filling lock. Flap plate (E) returns to "down" position when level reaches elevation 67′ and supply valve is closed.

would be present in the collection pool. The pool entrance was then closed, and covers were placed over the pool to keep the fish quiet during the hold over period which extended to the following morning. Thus, each fish present in the pool was held from 14 to 20 hours depending on the time it entered the pool and the time it subsequently left the pool to enter the experimental area on the following day. The assumption was then made that this procedure placed each fish in a relatively equal state of rest prior to its release into one of the endless fishways. Figures 15 and 16 present views of the collection pool when fish were entering and when the pool was covered during the hold over period.

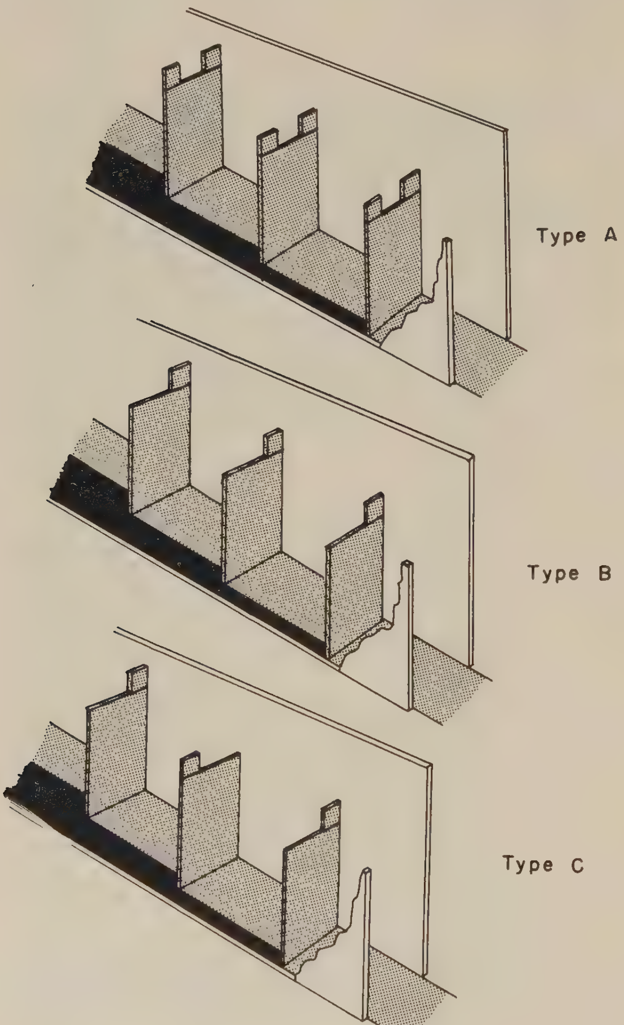


Figure 14.—Baffle placements showing notched, in-line, and alternate arrangements on weirs of 1-on-8-slope fishway.

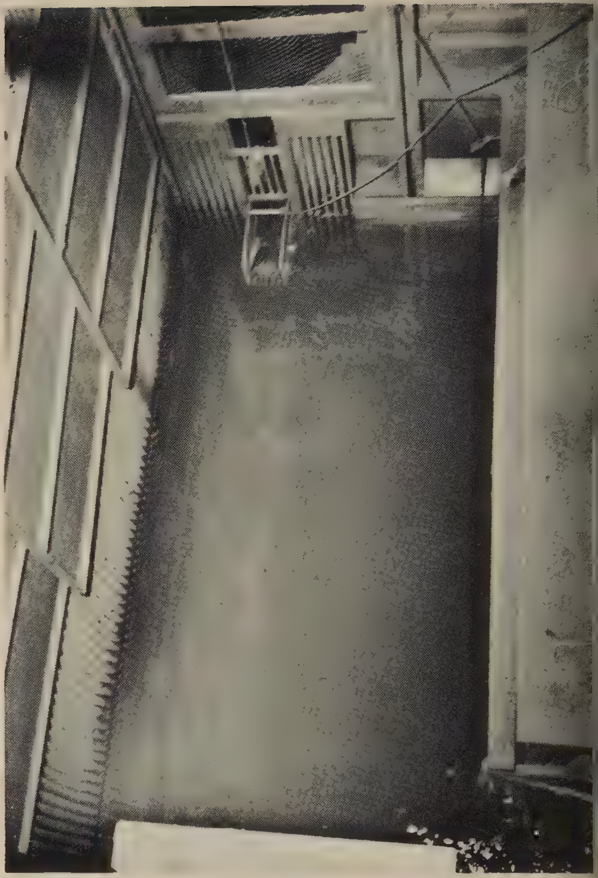


Figure 15.—Collection pool open for fish. Note fing
fyke at entry gate (upper center).

All fish remaining in the collection pool at 2:
p.m. each day were released into the bypa
channel (fig. 1) where they passed through t
laboratory and out into the Washington-sho
fishway. A brail on the floor of the collecti
pool was raised to ensure the exit of all remainin
fish previous to the entry of a new group for u
in the succeeding day's experiments.

During the latter part of the season this pr
cedure was modified by reducing the time t
fish were held in the collection pool to perio
not exceeding 6 hours and not less than 1 hou
The change in technique was made to save tim
This was done after a comparison of blood lacta
levels of fish held overnight with those of fis
held for only a few hours indicated no differen
in the physical states of the fish.

RELEASE AND TIMING

For each test, an individual fish from the colle
tion pool was permitted to enter the relea

FIGURE 16.—The fish collection pool with covers in place during hold over period.

compartment where it was observed briefly to determine species and physical condition. Fish bearing visible evidence of serious injuries, such as deep cuts or large abrasions, were rejected. There was no selection on the basis of size. The fish was then allowed to enter the introductory pool.

A fish swimming from the introductory pool into the fishway was the signal to start a test. The ascent was timed by a pair of observers who moved along with the fish as it proceeded up the fishway. A button switch was located on a handrail above each weir in the fishway, and as the fish passed from pool to pool, an observer pressed the button for the respective weir. This signal was in turn transmitted to an operations recorder that noted on a continuously revolving time tape the exact time of fish passage over each weir. Another attendant stood by to operate the lock and transfer the chronological record of ascent from the tape to an operations sheet.

When the fish entered the lock, the two observers promptly descended a walkway to the base of the lock and recorded the fish's movement as it entered pool 52 following discharge of lock water from elevation 67′ to 51′.

PERFORMANCE

Two types of performance tests were conducted during the June and July chinook and sockeye salmon migrations. One test consisted of permitting a fish to ascend through 104 pools (6½ circuits of the endless fishway) at which point the fish was immediately removed from the fishway and samples of blood and muscle tissue taken for biochemical analysis. The 104-pool ascent was an arbitrary choice but nevertheless in keeping with a simulated passage over a typical Columbia River dam. The foregoing tests were conducted on Sunday, Wednesday, Thursday, and Saturday of each week, and performance was measured in terms of minutes required to pass through 104 pools. On the remaining days—Monday, Tuesday, and Friday—a "prolonged ascent" test was carried on. These trials were designed to examine performance trends and biochemistry of fish subjected to a long ascent of generally more than 200 feet. As the latter tests often required lengthy periods of observation, they were normally discontinued after (a) approximately 13 hours or (b) after a fish had spent 60 minutes in a single pool.

Individuals removed from the fishway immediately following a specified ascent were called "terminated" fish as contrasted to "volitional" fish, which were those that stopped of their own volition for 60 minutes in a single pool and were then removed. Thus, the former can be considered as having been in an actively ascending state and the latter in a resting state at the time of their removal. All fish removed immediately after ascending 104 pools are, therefore, classified as terminated, while those removed after ascending in excess of 104 pools may be classed as terminated or volitional, depending on the circumstances of their removal. Occasionally, due to the time limitations or operational difficulties, a test was terminated before a 104-pool ascent was completed. There were also a number of instances in which fish came to a volitional stop before reaching 104 pools.

A special category—volitional-terminated—was later assigned to a limited group of summer chinook exhibiting what appeared to be obvious signs of stress or fatigue. These fish generally displayed a pattern of extremely rapid ascent followed by a drift or fallback movement which usually carried them completely down the fishway to the lowermost pool. At this point, the fish became impinged against the spillout grill in the lock, or if the lock was closed, it would appear against the spillout screen in pool 52. When this occurred the fish was removed from the fishway for immediate sampling of blood and tissue for biochemical analysis.

Performance trials conducted during August and September were confined solely to comparisons of the time required to make 104-pool ascents in the 1-on-8 and 1-on-16-slope fishways.

BIOCHEMISTRY

Immediately following the completion of a performance test, the fishway water supply was shut off and the fish was netted from the fishway and immobilized by a sharp blow on the head. In successive steps, and as rapidly as possible, 5 cc. of blood and several muscle-tissue cores were extracted (figs. 17 and 18) from the fish. Muscle cores were always taken from the area directly between the dorsal fin and the lateral line at a right angle to the left side of the fish. A heart puncture, made with a hypodermic syringe inserted through the body wall, served to extract the blood. Similar samples were taken each day from a control fish netted from the collection pool. Records were kept of the time required from the moment the fish was netted from the fishway until (1) the blood was extracted and (2) the tissue was weighed and placed in cold, 5-percent trichloroacetic acid.

After the blood and tissue samples were extracted, they were processed and placed in individual polyethylene containers and stored in a deep freeze for subsequent biochemical determinations. The length and sex of each fish were recorded, and the gonads were weighed for the purpose of determining sexual maturity. Lactate levels of the blood and muscle were determined by the method of Barker and Summerson as described in Hawk, Oser, and Summerson (1954, p. 622–624). King's modification of the Fiske and Subbarow method (King, 1932) was used to determine level of inorganic phosphate in the blood plasma and muscle tissue.

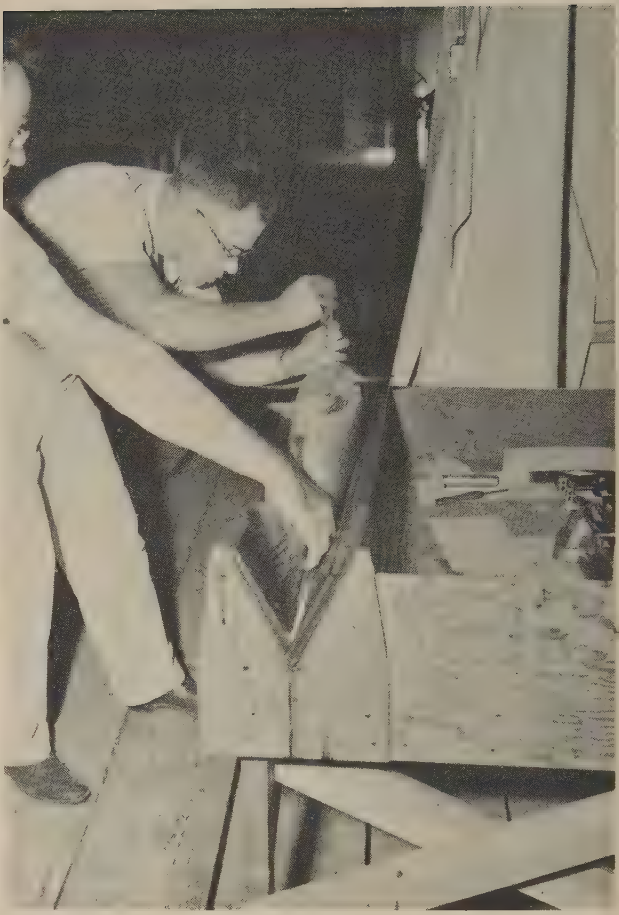


Figure 17.—Extracting blood from heart of a chinook salmon.

In addition to the foregoing, extracts of liver tissue and muscle tissue were also obtained for glycogen analysis, and a limited number of muscle tissue samples were taken for fat analysis. Glycogens were determined by the method of Montgomery (1957). Scales were also taken from many of the fish for subsequent age analysis. Special examinations for disease were made during August and September.

PERFORMANCE

Comparisons of the performance of chinook salmon, sockeye salmon, and steelhead trout with respect to slope consider (1) the passage

FIGURE 18.—Removing muscle core from side of chinook salmon.

time in minutes required to ascend a specified number of pools, (2) the pattern of movement or the "work-rest" relation, and (3) the willingness to ascend the respective fishways, the latter arbitrarily established as the percentage of fish negotiating 100 pools without stopping for 1 hour in a single pool. In addition, the work level at which fatigue might become apparent was examined by comparing mean rates of ascent at various levels of ascent in the fishway.

Examination of each of the foregoing aspects of performance will be treated in accordance with the prevailing fishway conditions as given in table 1; namely, (1) turn pools with rest areas, (2) turn pools turbulent, and (3) restricted weirs (1-on-8-slope).

Turn pools with rest areas (condition 1)

On June 9, 1958, tests in the endless fishways with rest conditions provided in the turns began with the passage of a limited number of chinook salmon. These were followed by sockeye salmon which continued in sufficient abundance for test purposes until July 20. A comparison of individual passage times of chinook and sockeye salmon through the 104-pool ascent level is given in table 2.

Chinook salmon ascending the 1-on-8-slope fishway required approximately 2.7 minutes per pool, while the mean rate in the 1-on-16-slope fishway was 2.0 minutes per pool. With the limited sample size, the difference in mean passage time for the 104-pool ascent is not statistically significant (table A–1). Because of the small sample size, however, there is a high risk of error in concluding that no true difference exists in the mean rates. A subsequent analysis comparing mean time per circuit (16 pools) showed a consistent (significant) difference between the time taken by chinooks ascending each of 6 circuits in

TABLE 2.—*Time in minutes to ascend 104 pools in endless fishways having slopes of 1 on 8 and 1 on 16 with turn pools providing rest areas (condition 1): Chinook salmon—June 9–20, sockeye salmon—June 21 to July 20, 1958*

Fish number	Chinook salmon		Sockeye salmon	
	1-on-8 slope	1-on-16 slope	1-on-8 slope	1-on-16 slope
1	321	148	167	162
2	430	198	155	155
3	152	237	149	180
4	251	171	177	184
5	207	334	192	217
6	362	308	198	129
7	273	329	204	123
8		135	167	126
9			130	173
10			144	303
11			144	254
12			167	94
13			197	127
14			198	213
15			169	173
16			179	187
17			176	158
18			179	180
19			151	182
20			150	138
21			175	132
22			134	214
23			151	139
Mean	285	232	168	175

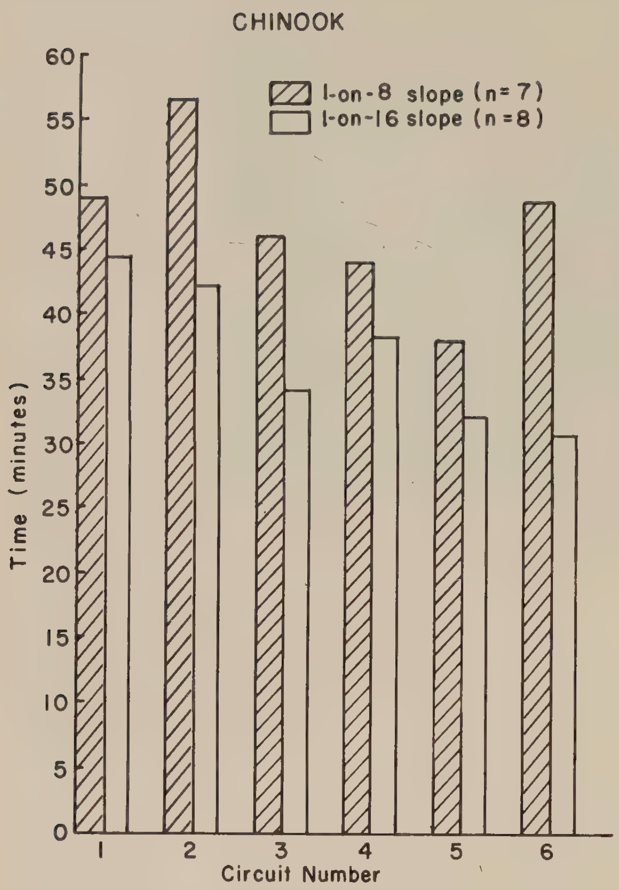


FIGURE 19.—Mean passage time per circuit (16 pools) taken by chinook salmon negotiating endless fishways having slopes of 1 on 8 and 1 on 16. June 9–21, 1958.

the two fishways. The average time per circuit in the 1-on-8-slope fishway was 44.1 minutes as compared to 36.4 minutes in the 1-on-16-slope fishway, or an average of 21 percent longer time in the 1-on-8 unit. (Comparative times per circuit are given in figure 19.)

Mean rates of ascent for sockeye over the 104-pool ascent level were virtually equal, being 1.6 minutes and 1.7 minutes per pool, respectively, in the 1-on-8- and 1-on-16-slope fishways.

The foregoing trials revealed a rather pronounced work-rest pattern of ascent, particularly in the fishway having a slope of 1 on 8. A somewhat similar but less exaggerated pattern of ascent was evidenced in the 1-on-16-slope fishway.

Because of the manner in which the endless fishways were constructed, every eighth pool was a turn pool. These turn pools created hydraulic conditions which were considerably different from those occurring in pools in the straightaway sections of the fishway. When the rates of ascent in both fishways were examined on the basis of time spent in each individual pool, the data indicate that the turn pools apparently were preferred resting areas. Chinook salmon ascending the 1-on-8-slope fishway passed through most of the straightaway pools in a matter of seconds and then usually remained in the turn pools for more than 15 minutes before starting to ascend again. In the 1-on-16-slope fishway, chinook spent an average of approximately 1 minute per pool in the straightaway sections and about 3 to 5 minutes in the turn polls (fig. 20).

Locking the fish appeared to cause relatively little delay in both fishways. The average time from the moment the fish crossed the upper weir until it actually left the lock was less than two minutes. The time spent in the pool following the lock was, however, greater than in straightaway pools. This may have been due to the change in hydraulic conditions encountered after leaving the lock.

A work-rest pattern of ascent similar to that of the chinook was evidenced by sockeye salmon ascending the endless fishways (fig. 21). In the 1-on-8-slope fishway, the average time per pool in the straightaway sections was about 23 seconds as compared to approximately 11 minutes per pool in each of the two turns. Sockeye ascending the fishway with a slope of 1 on 16 spent an average of 54 seconds in each of the straightaway pools and approximately 5 minutes in each turn pool.

The willingness to ascend the two fishway slopes appeared to be about equal when respective performances by chinook and sockeye were considered. Figure 22 gives the percentage of fish ascending 100 pools without stopping for 1 hour in an individual pool. Seven of 13 chinook in the 1-on-8 fishway and 8 of 12 in the 1-on-16 fishway completed the 100-pool ascent without prolonged stops in individual pools. Successful completions of the 100-pool ascent by sockeye were 25 out of 29, and 24 out of 31, respectively, in the 1-on-8 and 1-on-16-slope fishways. With the small number of fish in the samples, differences in the respective percentages completing the 100-pool ascent by species are not statistically significant.

To examine the possibility that ascending the experimental fishways might be fatiguing to fish, and that fatigue might be reflected in lowered per-

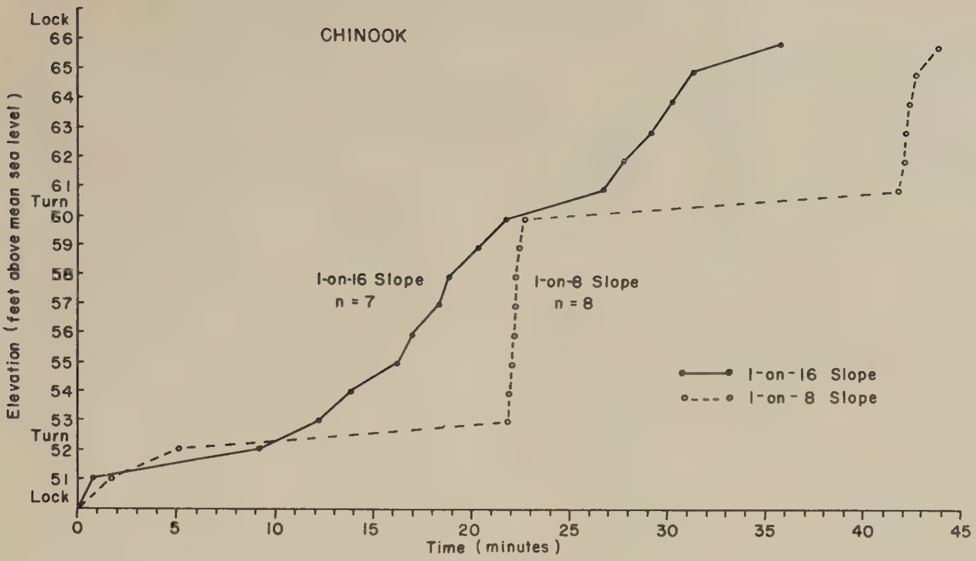


Figure 20.—Ascent pattern of chinook salmon in endless fishways having slopes of 1 on 8 and 1 on 16. Based on mean pool times of fish completing 6 or more circuits. June 9–21, 1958.

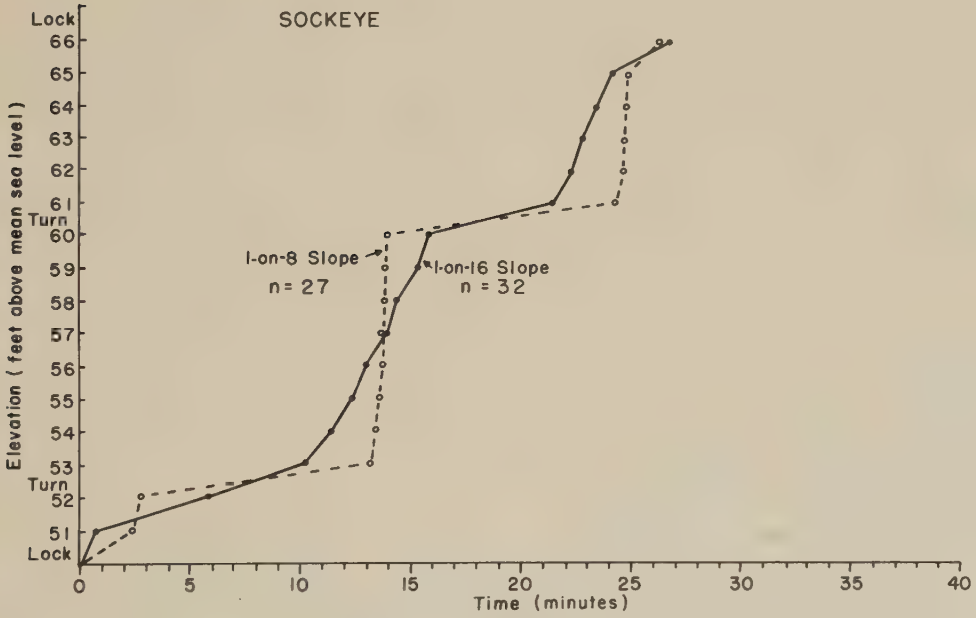


Figure 21.—Ascent pattern of sockeye salmon in endless fishways having slopes of 1 on 8 and 1 on 16. Based on mean pool times of fish completing six or more circuits. June 21 to July 20, 1958.

formance as the total work accomplished increased, the mean times per circuit for the first six circuits were plotted. These are given in figure 19 for chinook and in figure 23 for sockeye. Inspection of these graphs shows no evidence of a declining rate of movement in either fishway following successive ascent of each 16-pool circuit.

In the search for a work level at which fatigue might become apparent in the performance of the fish, a number of fish were permitted to ascend

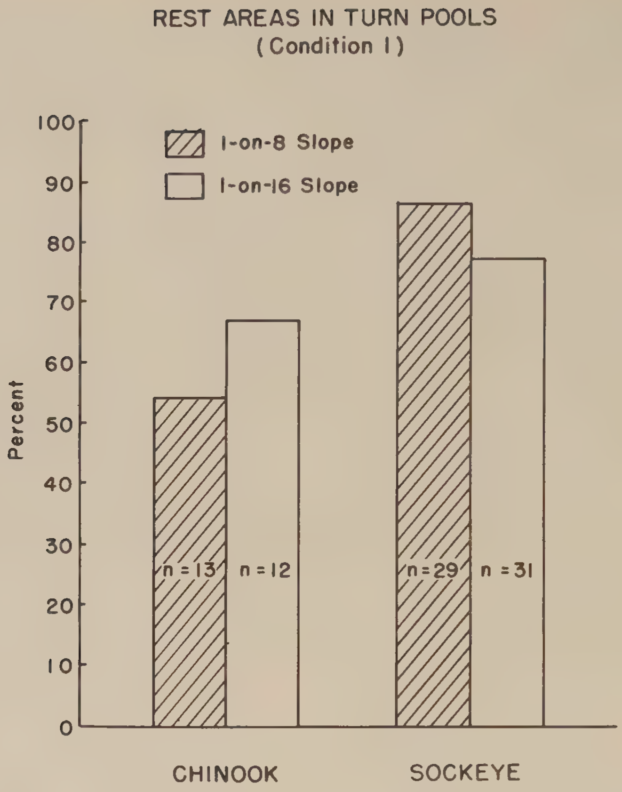


FIGURE 22.—Percentage of chinook and sockeye salmon ascending 100 pools in 1-on-8 slope and 1-on-16 slope endless fishways without stopping for 1 hour. Fishway condition 1 (rest areas in turns).

beyond the 104-pool ascent level in both fishways. Portions of the performance record of the fish that was permitted to ascend the greatest number of pools are shown in figure 24. This sockeye ascended the 1-on-8-slope fishway for 5½ days without stopping, and in that time it passed through 6,648 pools. There was no evidence of fatigue indicated by impaired performance until the fish had ascended more than 5,000 feet. The performance of this fish is discussed in greater detail by Collins, Gauley, and Elling (1962).

Perhaps the most significant finding to come from these extended ascent tests was the fact that salmonids are capable of ascending fishways of considerable height and do so without apparent physical stress.

Turn pools turbulent (condition 2)

While the preceding trials indicated that both chinook and sockeye salmon appeared to make satisfactory ascents in both the 1-on-8-slope fishway and the 1-on-16-slope fishway, the exaggerated work-rest pattern of ascent in the 1-on-8 slope posed a serious question.

Ideally, a pool-type fishway should function so that each pool provides a suitable resting area. This is important as it permits fish to distribute themselves throughout the fishway and does not overtax the physical capacities of even the less vigorous swimmers. If, however, only a small percentage of all pools in a fishway provide resting areas, we may then expect the fish to concentrate in these pools, eventually leading to the possibility of serious overcrowding. Also, if the rest pools are spaced at lengthy intervals, some fish may never complete their ascent because of their inability to pass from one rest area to another.

The foregoing considerations led us to examine the built-in pacing pattern which in effect was the result of the particular design of the endless fishways. The question to be answered was: Will fish ascending the endless fishways be able to pace themselves if the rest areas are eliminated from the turns? To accomplish this end, the turn pools were made so turbulent that they no longer provided satisfactory resting areas.

Passage of fish through the endless fishways having turbulent turn pools began on July 24 and continued until September 7. During this period, river temperatures ranged from 68° to 74° Fahrenheit. Chinook salmon and steelhead trout were the principal species tested in this period. A few sockeye and silver salmon (*O. kisutch*) were also passed during this time.

Table 3 presents the passage times of chinook and steelhead ascending the endless fishways with turbulent turn pools (condition 2). Both chinook and steelhead made significantly slower ascents in the 1-on-8-slope fishway than did their counterparts in the 1-on-16-slope unit (table A–1).

Most apparent in the foregoing tests was the obvious difficulty chinook salmon displayed in their ascent of the 1-on-8-slope fishway. Only 43 percent of all chinook entering the 1-on-8-slope fishway completed the 100-pool ascent without stopping in some pool for an hour (fig. 25).

Steelhead trout fared much better than chinook in the 1-on-8 fishway and were able to negotiate the 100-pool ascent without stopping in approximately the same proportion as those ascending the 1-on-16 fishway (fig. 25).

The difficulty encountered by chinook in the 1-on-8-slope could be traced to their inability to pace themselves when the rest areas were eliminated from the turns. Their pattern of ascent

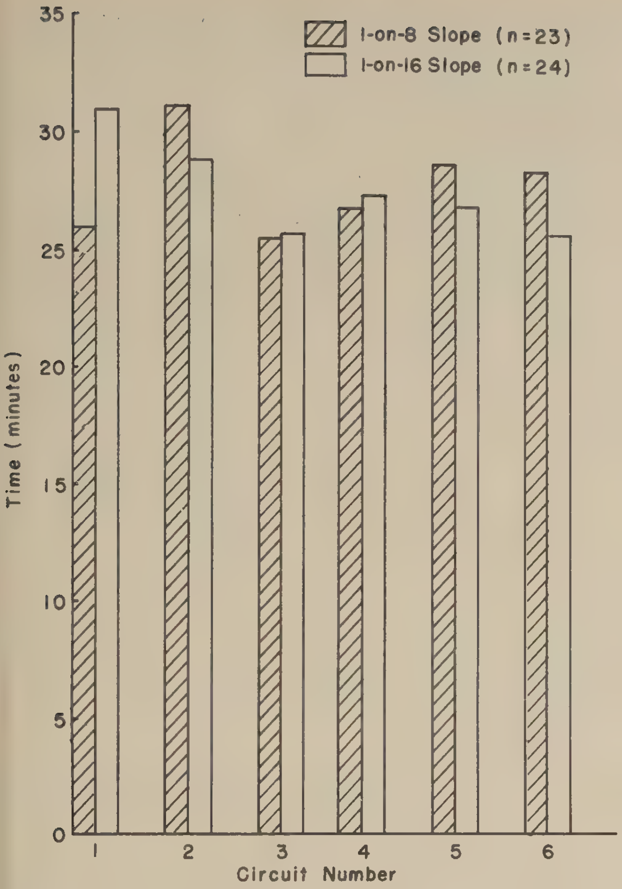


FIGURE 23.—Mean passage time per circuit (16 pools) taken by sockeye salmon negotiating endless fishways having slopes of 1 on 8 and 1 on 16. June 21 to July 20, 1958.

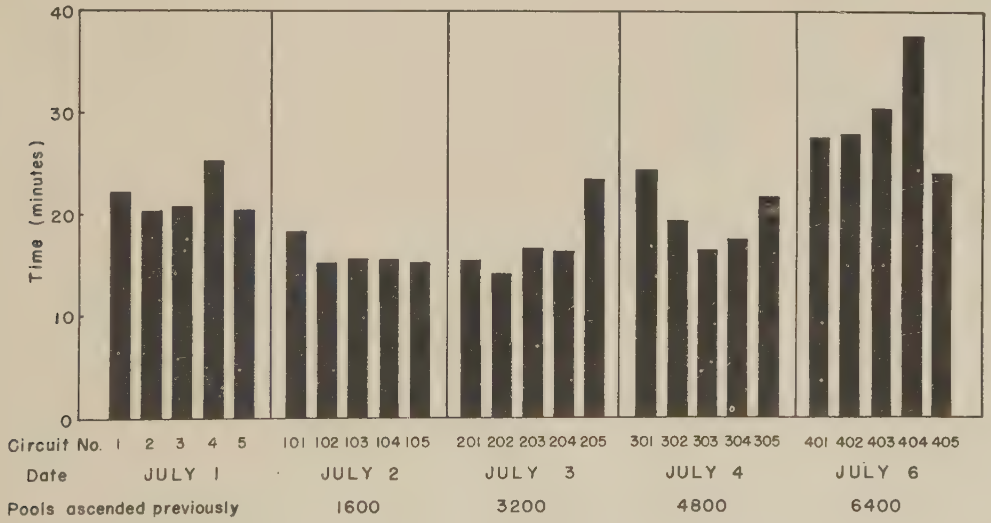


FIGURE 24.—Performance of an individual sockeye salmon in endless fishway with 1-on-8 slope. July 1–6, 1958.

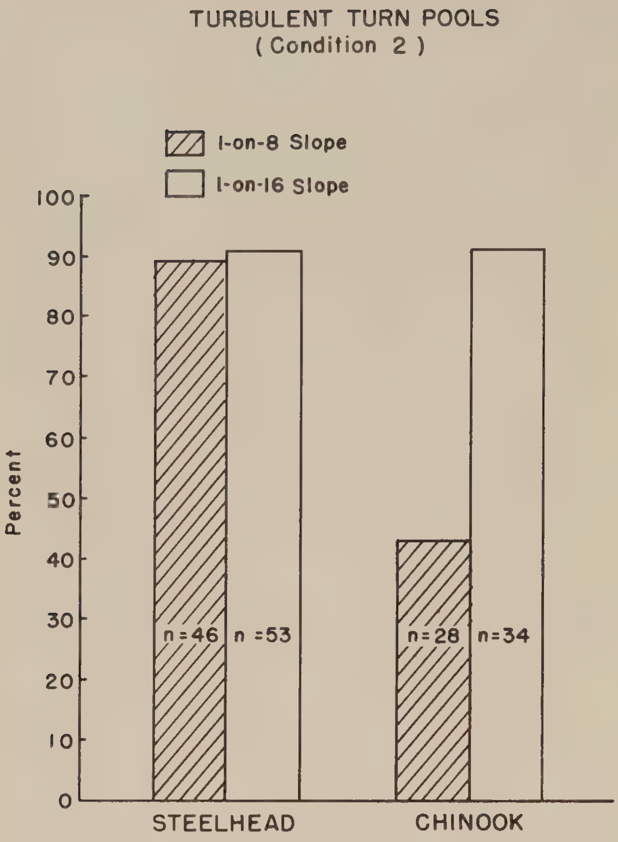


FIGURE 25.—Percentage of chinook salmon and steelhead trout ascending 100 pools in 1-on-8-slope and 1-on-16-slope endless fishways without stopping for 1 hour. Fishway condition 2 (turbulent turns).

was again similar to that evidenced in the earlier trials (fig. 19) with the exception that the rest was usually taken in a straightaway pool after a very rapid ascent through a number of preceding pools. However, in several instances chinook salmon were observed to prolong a swift ascent for approximately 16 to 20 pools. At this point they appeared to be in a state of exhaustion and on occasion were actually swept back down the fishway, seemingly lacking the strength to maintain equilibrium within a pool. Subsequent examination of the biochemical state of these fish confirmed the observation that they were experiencing physical stress.

In contrast to chinook, steelhead did not experience the same difficulty in pacing their movements through the 1-on-8 fishway. A comparison of mean ascent times by individual pools in the two fishways is given in figure 26. While steelhead required more time to ascend the 1-on-8 slope, the work-rest pattern was not greatly divergent from that evidenced in the 1-on-16 slope.

Restricted Weirs (1-on-8 Slope) vs. Condition 2 (1-on-16 Slope)

Because of the apparent inability of a large percentage of the chinook to pace themselves successfully in the 1-on-8-slope fishway when resting areas had been removed from the turn pools, an attempt was made to pace the fish by altering the hydraulics in all pools of the fishway. This was done by restricting the water flows over the weirs by means of baffles. The reduction in the total volume of water entering each pool resulted in considerably reduced turbulence and also created a definite lateral component in the pool flow pattern. The three methods used to

TABLE 3.—*Time in minutes to ascend 104 pools in endless fishways having slopes of 1 on 8 and 1 on 16 with turbulent turn pools (condition 2)*

[Chinook salmon—July 24 to September 7; steelhead trout—July 24 to September 2, 1958]

Fish number	Chinook		Steelhead	
	1-on-8 slope	1-on-16 slope	1-on-8 slope	1-on-16 slope
1	275	197	182	169
2	227	261	213	139
3	178	107	243	212
4	208	111	306	161
5	220	122	250	245
6	303	285	178	193
7	300	307	247	247
8	232	157	236	286
9	190	159	154	133
10	374	129	251	100
11	244	249	221	97
12	314	115	174	171
13	----------	169	271	109
14	----------	121	170	131
15	----------	111	182	145
16	----------	183	165	166
17	----------	198	244	206
18	----------	165	252	116
19	----------	241	148	116
20	----------	166	144	105
21	----------	202	202	118
22	----------	171	181	136
23	----------	205	378	166
24	----------	200	139	149
25	----------	153	205	145
26	----------	264	196	180
27	----------	187	331	123
28	----------	207	187	139
29	----------	----------	236	111
30	----------	----------	363	106
31	----------	----------	163	127
32	----------	----------	293	135
33	----------	----------	140	258
34	----------	----------	280	105
35	----------	----------	219	177
36	----------	----------	266	190
37	----------	----------	208	174
38	----------	----------	----------	119
39	----------	----------	----------	143
40	----------	----------	----------	131
41	----------	----------	----------	149
42	----------	----------	----------	175
43	----------	----------	----------	123
44	----------	----------	----------	146
45	----------	----------	----------	131
46	----------	----------	----------	212
Mean	255	184	222	155

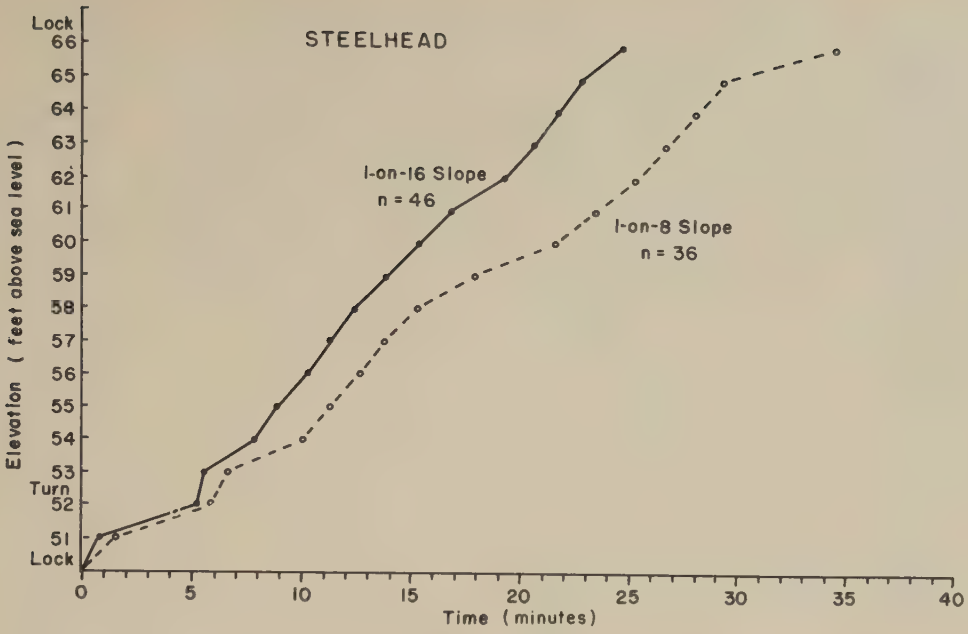


FIGURE 26.—Ascent pattern of steelhead trout in endless fishways having slopes of 1 on 8 and 1 on 16. Based on mean pool times of fish completing 6 or more circuits. Condition 2 (turbulent turn pools).

trict flows are shown in figure 14. These fle arrangements were applied only to the 1-8 fishway. Condition 2 (table 1) continued to vail in the 1-on-16 fishway during these tests.)n September 10 and 11, several exploratory ls utilizing condition 2A (center-notched weir 14) revealed an improved work-rest pattern the 1-on-8 fishway. The rate of ascent and lingness to ascend, however, did not compare orably with that shown in the 1-on-16 fishway. ther than continue further experiments with design, we made a series of tests during the ainder of September employing the other baffle angements, in-line baffles B and alternating fles C (fig. 14).

A comparison of chinook salmon passage times the two fishways for the period September -29 is given in table 3. While the mean ascent e of chinook in the 1-on-8-slope fishway with ine baffles (condition 2B) was significantly wer (table A–1) than that in the 1-on-16-slope way, the final trials employing alternating fles (condition 2C) in the 1-on-8-slope fishway v no difference in the time of ascent in the two ways.

he patterns of movement resulting in the egoing tests are shown in figures 27 and 28. Notably, chinook salmon paced their movements in the 1-on-8-slope fishway as well as they did in

TABLE 4.—*Chinook salmon passage time in minutes to ascend 104 pools in endless fishways with slopes of 1 on 8 and 1 on 16*

[Weir baffles in-line (condition 2B) and alternating (condition 2C) in the 1-on-8 fishway. Turbulent turn pools (condition 2) in the 1-on-16 fishway.]

Fish number	September 12–23		September 24–29	
	1-on-8 slope condition 2B	1-on-16 slope condition 2	1-on-8 slope condition 2C	1-on-16 slope condition 2
1	382	193	183	182
2	339	190	108	258
3	233	223	112	91
4	134	134	133	153
5	211	210	138	178
6	178	132	165	182
7	272	147	165	123
8	314	182	175	140
9	157	146	178	135
10	317	138	---	---
11	209	236	---	---
12	125	206	---	---
13	251	111	---	---
14	188	106	---	---
15	159	264	---	---
16	179	166	---	---
17	139	201	---	---
18	153	103	---	---
19	191	172	---	---
20	113	127	---	---
21	243	188	---	---
22	173	131	---	---
23	167	169	---	---
24	224	153	---	---
25	179	136	---	---
26	203	184	---	---
27	---	122	---	---
28	---	177	---	---
29	---	136	---	---
30	---	128	---	---
31	---	176	---	---
Mean	209	164	151	160

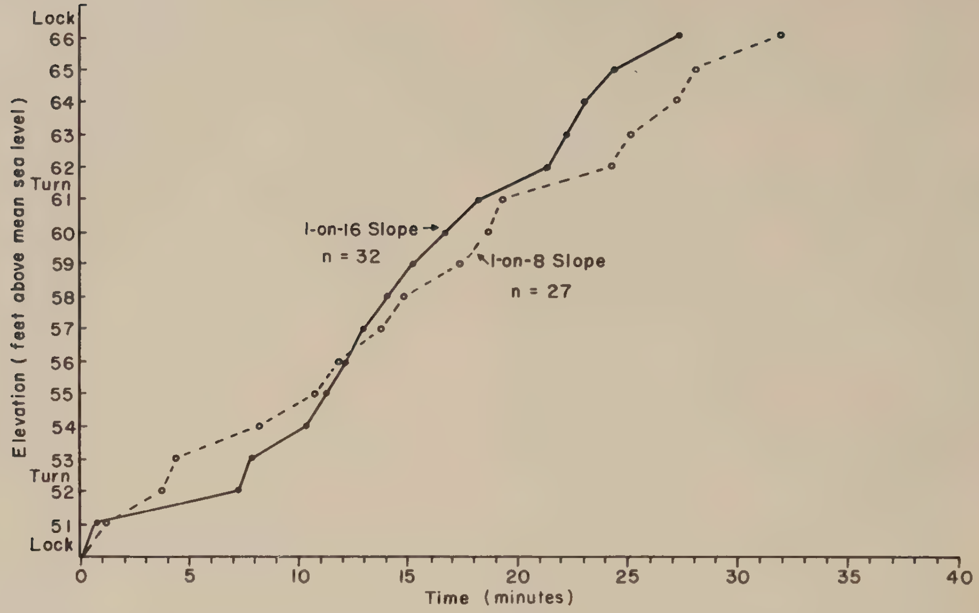


FIGURE 27.—Ascent pattern of chinook salmon in endless fishways having slopes of 1 on 8 (condition 2B, in-line baffles) and 1 on 16 (condition 2). Pool times derived from mean of 6 trips. September 12–23, 1958.

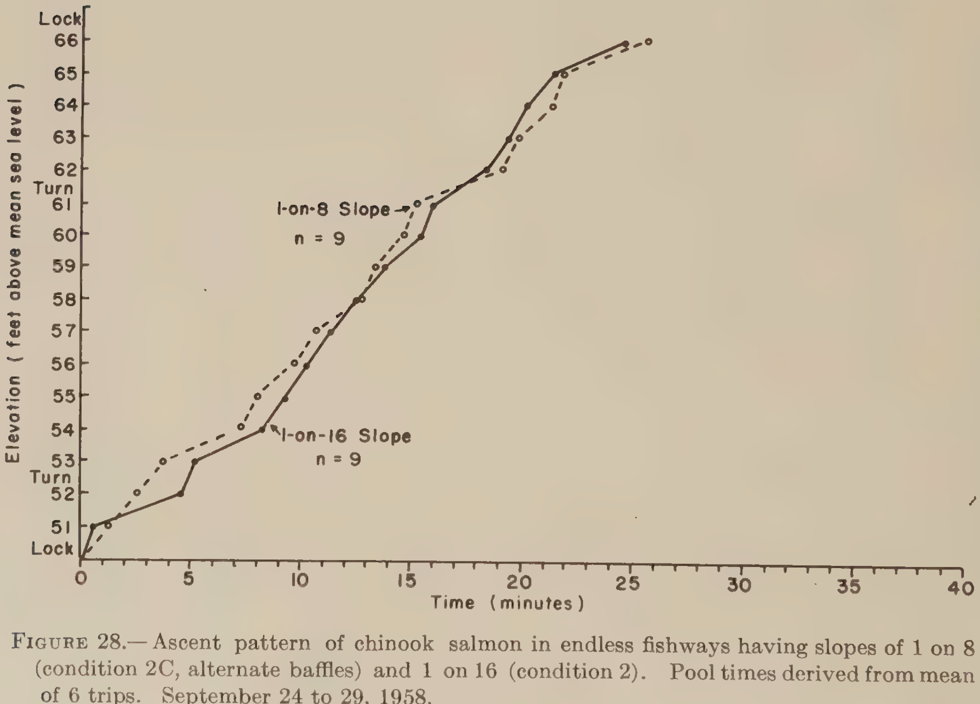
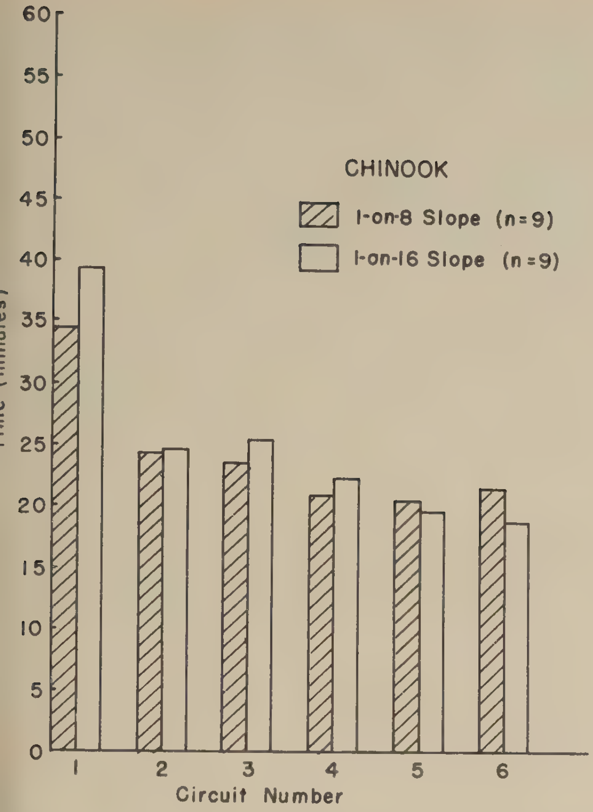


FIGURE 28.—Ascent pattern of chinook salmon in endless fishways having slopes of 1 on 8 (condition 2C, alternate baffles) and 1 on 16 (condition 2). Pool times derived from mean of 6 trips. September 24 to 29, 1958.



IGURE 29.—Mean passage time per circuit taken by chinook salmon negotiating endless fishways having slopes of 1 on 8 (condition 2C, alternate baffles) and 1 on 16 (condition 2). September 24–29, 1958.

ne 1-on-16-slope fishway. Evidence of the xaggerated work-rest pattern was completely cking in both fishways.

Another encouraging aspect of the performance the 1-on-8 fishway was that all chinook tested hen conditions 2B and 2C prevailed completed e 100-pool ascent without stopping in an invidual pool for 1 hour. In the same period, 93 ercent of all chinook entering the 1-on-16 fishway assed the 100-pool ascent level without stopping.

Comparisons of the mean passage time per rcuit for first 6 circuits show no evidence that inook salmon were tiring after successive trips either fishway (fig. 29). By inspection the first rcuit appears to have required the longest time, d thereafter the time per circuit was about the me.

BIOCHEMISTRY

In further search for evidence that one fishway ght be more fatiguing than another, lactate d inorganic phosphate levels were measured in the blood and muscle of the experimental fish. The basis for study of these chemical compounds is well documented in biochemical literature. Black (1958a) has prepared an excellent summary on the subject of chemical correlates associated with muscular activity and recovery from fatigue in fishes. The four correlates selected for study in this experiment have all been shown to increase in level following muscular activity. The degree of muscular activity, i.e., minimal, moderate, and maximal, has been somewhat more difficult to assess because of the lack of recognizable standards. In this study, we reasoned that if the ascent of one fishway were to require more effort than that in another, the difference would be reflected in the chemistry of the fish. In addition, a comparison between the chemistry of exercised and unexercised fish (controls) was expected to provide some insight on the degree of muscular activity that may be necessary in the ascent of fishways.

In this study, the unexercised controls may be considered to represent a minimal state of activity. It should be pointed out, however, that these fish were by no means quiescent since they were free to swim about in the collection pool prior to their removal. To prepare a control fish for chemical extractions, it was necessary to net and then lift the fish approximately 14 feet to floor level in the laboratory. While this was accomplished as rapidly and efficiently as possible, some struggling did occur before the fish could be immobilized. The combination of these circumstances conceivably may have produced somewhat higher chemical values than would normally be expected in unexercised fish.

The majority of fish removed from the fishway while actively ascending (terminated treatments) were expected to be representative of an intermediate stage of muscular activity in the broad range between minimal and maximal activity. Again, the circumstances of fish removal from the fishway may have had some effect on the chemical values. Since most of the terminated treatments were taken from the shallow, upper turn pool, netting and immobilization of these fish were accomplished quite rapidly and generally with a minimum of struggling.

Fish stopping for 1 hour in an individual pool (volitional treatments) were of particular interest in this study inasmuch as the chemistry of these fish would be expected to yield certain information on the degree to which fish might recover from their exertions in the ascent of a fishway. Removal of these fish was not always accomplished as easily as was the case with the terminated treatments. If a fish stopped at a point other than in the turns or the lock, it was necessary to net the fish from a pool which was 6 feet deep. This was readily accomplished if the fish surfaced when the fishway water supply was shut off, but if the fish remained in the depths of the pool, it was occasionally necessary to chase the fish some time before capture.

Capture and removal of the volitional-terminated treatments were achieved with little or no struggling as these fish were incapable of vigorous evasive action, probably due to exhaustion resulting from a rapid and improperly paced ascent. As will be pointed out later in the text, the chemistry of these fish suggests they may have been subjected to a period of maximal activity.

The following analysis of the biochemical determinations is made in accordance with the prevailing fishway conditions as was done under the section on performance. As may be seen in the subsequent tables, lactate of whole blood appears to have been the most sensitive of the four chemical measurements obtained.

Turn pools with rest areas (condition 1)

Summaries of the biochemical measurements on chinook and sockeye salmon ascending the 1-on-8 and 1-on-16-slope fishways when condition 1 prevailed appear in tables 5 and 6. Inspection of tables 5 and 6 indicates that levels of blood lactate in exercised fish terminated while still actively moving and regardless of the height ascended were approximately equal in both fishways. Blood lactates of terminated treatments were significantly higher than the unexercised controls (table 7). With the exception of a few fish having special case histories, none of the blood lactates from exercised fish exceeded 100 mg. percent. Levels of whole blood lactate in terminated treatments of exercised sockeye were significantly higher than similarly treated chinook salmon (1-on-8 slope, $t=3.757$, d.f. 26, $P<.01$; 1-on-16 slope, $t=2.516$, d.f. 25, $.02>P>.01$).

The blood lactate level of fish that stopped for an hour on their own volition (at a variety of ascent levels) did not differ significantly from that of the unexercised control fish (table 7). This suggests that the fish were able to rest in either fishway slope, and that they had recovered from exercise within an hour.

Levels of muscle lactate and inorganic phosphate of the blood plasma and muscle tissue indicate the possibility that similar patterns may exist for these measurements. However, the sample sizes are so small and the variation between individuals so great that only gross differences are detectable with any degree of confidence.

TABLE 5.—*Biochemistry of chinook salmon ascending 1-on-8- and 1-on-16-slope endless fishways with 36-inch weirs and turn pools providing rest areas (condition 1)*

[Mean values in mg. percent, June 9–21, 1958 [1]]

Substance	1-on-8 slope				1-on-16 slope				Controls	
	Number of fish	Terminated	Number of fish	Volitional	Number of fish	Terminated	Number of fish	Volitional	Number of fish	Unexercised
Lactate of whole blood	7	39.1	6	29.3	8	38.4	4	23.1	11	24.3
Lactate of muscle tissue	7	318	6	293	8	334	4	347	11	306
Inorganic PO_4 of blood plasma	7	11.6	6	10.3	8	10.7	4	11.4	11	12.2
Inorganic PO_4 of muscle tissue	7	183	6	163	8	179	4	173	11	172

[1] Mean daily water temperature during test period: 63° F. (17.2° C.).

TABLE 6.—*Biochemistry of sockeye salmon ascending 1-on-8- and 1-on-16-slope endless fishways with 36-inch weirs and turn pools providing rest areas (condition 1)*

[Mean values in mg. percent, June 21–July 20, 1958 [1]]

Substance	1-on-8 slope				1-on-16 slope				Controls	
	Number of fish	Terminated	Number of fish	Volitional	Number of fish	Terminated	Number of fish	Volitional	Number of fish	Unexercised
Lactate of whole blood	21	63.5	9	25.0	19	57.9	11	28.5	19	21.8
Lactate of muscle tissue	20	370	10	261	18	387	12	332	18	298
Inorganic PO_4 of blood plasma	21	14.0	10	10.4	17	13.3	11	12.9	18	11.8
Inorganic PO_4 of muscle tissue	21	151	10	152	19	139	12	147	18	137

[1] Mean daily water temperature during test period: 67° F. (19.4° C.).

TABLE 7.—*Tests of significance between mean blood lactate levels (mg. percent) in exercised and unexercised chinook and sockeye salmon in endless fishways with slopes of 1-on-8 and 1-on-16 (condition 1)*

Fishway slope	Species	Exercised				Unexercised		Degrees of freedom	Value of *t*
		Number of fish	Terminated	Number of fish	Volitional	Number of fish	Control		
on-8	Chinook	7	39.1			11	24.3	16	2.60*
	Chinook			6	29.3	11	24.3	15	.94 N.S.
	Sockeye	21	63.5			19	21.8	38	10.43**
	Sockeye			9	25.0	19	21.8	26	.36 N.S.
on-16	Chinook	8	38.4			11	24.3	17	2.33*
	Chinook			4	23.1	11	24.3	13	.18 N.S.
	Sockeye	19	57.9			19	21.8	30	7.06**
	Sockeye			11	28.5	19	21.8	28	1.33 N.S.

*Significant at 0.05 level.
**Significant at 0.01 level.
N.S. Not significant.

urn Pools Turbulent (Condition 2)

Chinook salmon and steelhead trout were the rincipal species tested during the period of July 4 to September 7 when the turbulent turn pools condition 2) were employed in the endless fishways.

Note is made of the abnormally high river emperatures prevailing during this time. At Bonneville, records[3] show these ranged from 8°–74° Fahrenheit (20°–23.3° C.). The mean August temperature (71.7° F.) was the highest on ecord since construction of the dam. During he 20-year period 1938 to 1957, mean August water temperatures ranged from 63° to 69.7° F., with a 20-year mean of 67.5° F.

Summary data covering the biochemistry of hinook and steelhead ascending the endless fishways when condition 2 prevailed are presented, espectively, in tables 8 and 9. A few sockeye were also tested in the fishways during the above eriod, but the limited data from these tests were not considered in this analysis.

Examination of tables 8 and 9 reveals several oints of interest with respect to the levels of actate of whole blood. Mean blood lactate evels of both chinook and steelhead, terminated while actively ascending the fishways, appear to e somewhat higher in the 1-on-8 slope than in he 1-on-16 slope. These differences, however, were not significant: chinook—$t=1.735$, d.f. 1, $.09<P<.10$; steelhead—$t=1.213$, d.f. 56, $2<P<.3$. Blood lactates of the terminated ish were significantly higher than those of the ontrol fish (table 10) as they were in the earlier rials under condition 1. Again, a similar but ot always consistent trend was evidenced by the lactate of muscle and inorganic phosphate of blood plasma and muscle tissue.

By inspection, mean blood lactates of volitional treatments (fish that had exercised and stopped for 1 hour in a fishway pool) of both chinook and steelhead are considerably higher than those of the control treatments; however, because of the small sample sizes involved and the unequal variance between samples, the differences in lactate level generally were not significant (table 10). In the case of chinook salmon ascending the 1-on-8-slope fishway, the blood lactate of volitional treatments was significantly higher than that of the controls. This represents a clear departure from the trend evidenced in the earlier trials under condition 1 when volitional treatments yielded blood lactate levels quite comparable to those of the controls. It may also be noted that the blood lactate levels for exercised chinook salmon (terminated and volitional) in both fishways were higher under condition 2 than in condition 1 (tables 5 and 8), but the differences were statistically significant only for volitional treatments in the 1-on-8-slope fishway.

Whether or not the comparatively high blood lactate levels under condition 2 are linked in some way with the prevailing high water temperatures during this period is a matter of speculation. Examination of the work pattern of the volitional fish in both fishways shows the pattern was generally that of rapid ascent followed by the 1-hour stop. Presumably the fish had not fully recovered from the vigorous exercise which preceded the volitional stop. Additional studies will be necessary to determine the relationship between water temperature and blood lactate levels in exercising fish.

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[3] Daily operation reports, U.S. Army Corps of Engineers, Bonneville Dam.

TABLE 8.—*Biochemistry of chinook salmon ascending 1-on-8 and 1-on-16-slope endless fishways with 36-inch weirs and turbulent turn pools (condition 2)*

[Mean values in mg. percent, July 24–September 7, 1958 [1]]

Substance	1-on-8 slope				1-on-16 slope				Controls	
	Number of fish	Terminated	Number of fish	Volitional	Number of fish	Terminated	Number of fish	Volitional	Number of fish	Unexercised
Lactate of whole blood	12	51.6	12	89.1	31	42.0	3	81.5	13	26.
Lactate of muscle tissue	12	329	12	324	31	315	3	376	13	295
Inorganic PO_4 of blood plasma	6	9.0	9	12.8	19	8.8	3	14.2	8	9.
Inorganic PO_4 of muscle tissue	11	163	12	170	31	164	3	164	13	159

[1] Mean daily water temperature during test period: 71° F. (21.7° C.).

TABLE 9.—*Biochemistry of steelhead trout ascending 1-on-8 and 1-on-16-slope endless fishways with 36-inch weirs and turbulen turn pools (condition 2)*

[Mean values in mg. percent, July 24–September 2, 1958 [1]]

Substance	1-on-8 slope				1-on-16 slope				Controls	
	Number of fish	Terminated	Number of fish	Volitional	Number of fish	Terminated	Number of fish	Volitional	Number of fish	Unexercised
Lactate of whole blood	42	42.4	5	57.1	47	34.5	5	46.5	29	21.
Lactate of muscle tissue	45	350	5	401	49	371	6	391	30	326
Inorganic PO_4 of blood plasma	42	10.4	5	11.0	44	10.2	5	11.9	29	9.
Inorganic PO_4 of muscle tissue	45	167	5	162	47	165	6	171	30	164

[1] Mean daily water temperature during test period: 72° F. (22.2° C.).

TABLE 10.—*Tests of significance between mean levels of blood lactate (mg. percent) in exercised and unexercised chinook and steelhead ascending 1-on-8 and 1-on-16-slopes endless fishway (condition 2)*

Fishway slope	Species	Exercised				Unexercised		Degrees of freedom	Value of *t*
		Number of fish	Terminated	Number of fish	Volitional	Number of fish	Control		
1-on-8	Chinook	12	51.6			13	26.0	18	3.96**
	Chinook			12	89.1	13	26.0	13	5.34**
	Steelhead	42	42.4			29	21.6	55	5.36**
	Steelhead			5	57.1	29	21.6	4	1.30 N.S.
1-on-16	Chinook	31	42.0			13	26.0	42	3.48**
	Chinook			3	81.5	13	26.0	2	2.33 N.S.
	Steelhead	47	34.5			29	21.6	75	4.821**
	Steelhead			5	46.5	29	21.6	4	1.52 N.S.

**Significant at the 0.01 level.
N.S. Not significant.

Attention is called to the biochemistry of a special group of chinook salmon that displayed visible evidence of physical stress during their ascent of the 1-on-8-slope fishway. For lack of a more appropriate term, this group was classified "volitional-terminated" and includes only those individuals evidencing an obvious loss of equilibrium, i.e., an inability to maintain position in the fishway following a period of exercise. In all cases, these fish made extremely rapid ascents of a succession of pools (several seconds per pool) at which point they appeared to reach a state of exhaustion and drifted completely down the fishway to the lowermost pool where they became impinged against the spillout screen. Analysis of the biochemistry of these fish appears in table 11. While there are exceptions, notably in the levels of inorganic phosphate of the plasma and muscle tissue, the majority of these measures clearly affirm the observation that the fish were experiencing physical stress. The levels of blood lactate appear to be the most consistent in indicating the state of fatigue. All approached or exceeded 100 mg. percent, which from our experience to date is well above the blood lactate response expected in fish exhibiting a uniform work-rest pattern during ascent of a fishway.

Four of the five fish listed in table 11 were tested during the period of high river temperatures and when condition 2 prevailed in the 1-on-8-slope fishway. The lone entry occurring during the earlier period, when condition 1 applied

ABLE 11.—*Biochemistry of chinook salmon taken from the 1-on-8-slope endless fishway following evidence of physical stress, 1958*

Fish number	Date	Temperature F.	Temperature C.	Fishway condition	Substance—mg. percent: Lactate of blood	Lactate of muscle	Inorganic PO_4 of plasma	Inorganic PO_4 of muscle
		Degrees	*Degrees*					
	June 13	62	16.7	1	123.1	347	16.5	163
	July 25	72	22.2	2	168.2	474	17.4	210
	July 28	74	23.3	2	120.6	630	22.6	165
	July 31	73	22.8	2	98.0	245	16.3	153
	Aug. 18	71	21.7	2	105.4	401	11.9	126
Mean		70	21.3		123.1	419	16.9	161

ABLE 12.—*Biochemistry of chinook salmon ascending 1-on-8 (condition 2B) and 1-on-16-slope (condition 2) endless fishways*

[Mean values in mg. percent, September 12–23, 1958 [1]]

Substance	1-on-8 slope: Number of fish	Terminated	Number of fish	Volitional	1-on-16 slope: Number of fish	Terminated	Number of fish	Volitional	Controls: Number of fish	Unexercised
actate of whole blood	[2] 20	35.5	0		24	36.5	2	33.0	12	19.7
actate of muscle tissue	20	281	0		24	303	2	403	12	315
iorganic PO_4 of blood plasma	20	10.1	0		17	9.4	2	9.4	12	10.0
iorganic PO_4 of muscle tissue	18	156	0		24	153	2	161	12	152

[1] Mean daily water temperature during test period: 66° F. (18.9° C.).

[2] Includes 1 fish ascending less than 104 pools.

ras a 40-pound 6-ounce male, the largest fish ncountered in all of the tests.

estricted Weirs (1-on-8 Slope) vs. Condition 2 (1-on-6 Slope)

Following structural adjustments designed to educe turbulence in the 1-on-8-slope fishway, a eries of biochemical measurements was obtained rom chinook salmon tested during the period of eptember 12 to 23, inclusive. These were comared with similar measurements from fish ascendng the 1-on-16-slope fishway which remained unhanged structurally from the previous period condition 2, July 24 to September 7). Results f these analyses appear in table 12. With a single xception, all terminated treatments include fish hat had completed an ascent of 104 pools. Examnation of the blood lactate levels of fish termiated immediately after exercise shows there was o difference in the lactate response of fish ascendng either the 1-on-8- or 1-on-16-slope fishways. lood lactate levels of terminated treatments in he 1-on-16-slope fishway ranged from 16.8 to 62.5 g. percent while those in the 1-on-8-slope fishay ranged from 20.1 to 48.3 mg. percent. Thus, he installation of weir baffles in the 1-on-8-slope shway appears to have created hydraulic condiions which were no more fatiguing than those in he 1-on-16-slope fishway.

The blood lactate of terminated treatments in both fishways was significantly higher than that of the controls. A slightly less than twofold increase was indicated.

Levels of muscle lactate and inorganic phosphate of the blood plasma appear to be less sensitive than the whole blood lactate measurements, but in general they indicate comparable work levels for fish ascending either fishway.

Recovery following exercise in fishways

A number of investigators have demonstrated delayed effects due to strenuous exercise that have resulted in mortalities of test fish (von Buddenbrock, 1938; Secondat and Diaz, 1942; Bates and Vinsonhaler, 1957; Black, 1957; Parker and Black, 1959; Parker, Black, and Larkin, 1959). Black (1958b) in summarizing available evidence states that death in fish occurs ½ to 3 hours following severe muscular activity and is the result of a combination of adverse factors as yet not completely described. Parker and Black (1959) found that mortalities among troll-caught chinook salmon in salt water occurred from 1 to 7½ hours following capture and that death was significantly correlated with high blood levels of lactic acid.

To explore the possibility of serious latent or delayed effects due to exercise in the fishways, a number of exercised fish were held overnight in a relatively quiet fishway pool (upper turn pool, elevation 61′). The procedure followed during the holding period was as follows: at the moment the fish entered the 105th pool, screen barriers were placed on the upstream and downstream weirs of the pool. Flows in the fishway were then reduced to approximately .25 c.f.s. and the pool was completely covered with plywood sheets. On the following morning, generally between 12 and 16 hours after the fish had entered the pool, the plywood covers were removed and the fish were carefully netted and immobilized in preparation for the usual biochemical extractions.

Eight chinook salmon in each fishway were held overnight in the foregoing manner, and in each instance no mortality was observed. Analysis of the biochemistry of these fish appears in table 13. In general, it may be seen that the condition of these fish approximated that of the controls for the same period, and on the basis of these limited observations, at least, we consider it very unlikely that delayed mortality would result from the physical exertion needed to ascend a properly designed fishway. This appears to be in keeping with investigations by Parker, et al. (1959), who in working with nonfeeding silver salmon in fresh water, found no mortalities and lower lactate levels than occurred under similar circumstances in sea water.

TABLE 13.—*Biochemistry of chinook salmon held overnight (12–16 hours) after ascending 104 pools in endless fishways with slopes of 1-on-8 and 1-on-16, September 15–23, 1958*

[Mean values in mg. percent]

Substance	1-on-8 slope		1-on-16 slope		Controls	
	Number of fish[1]	Held after exercise	Number of fish[1]	Held after exercise	Number of fish[1]	Unexercised
Lactate of whole blood	7	24.5	8	18.7	9	19.4
Lactate of muscle tissue	7	254	8	277	9	308
Inorganic PO_4 of blood plasma	6	8.4	7	9.4	9	10.1
Inorganic PO_4 of muscle tissue	7	172	8	158	9	154

[1] Eight fish were held overnight in each fishway but certain measurements were not obtained from all fish.

Other factors affecting performance and biochemical state

In the preceding discussions, all comparisons of performance in the two fishways (1-on-16 and 1-on-8 slopes) have been based on the assumption that the individual capacity to perform was randomly distributed among all fish. We have previously noted that individual fish were entered into each fishway with no distinction as to size, sex, or visible physical condition. Only those fish having obvious severe physical injuries were rejected.

Aside from the slope and prevailing hydraulics of the respective fishways, other factors which may have influenced performance and biochemical state are the size, sex, maturity, racial origin, and physical condition (injured or diseased) of the fish. Water temperature and turbidity possibly may also be related to performance and biochemical state, but as a common water source served both fishways, these variables need not be considered in evaluating respective ascents in the two fishways.

In the recent tests, data are available to permit limited analysis of the effects of size, sex, and maturity of the fish on performance and biochemical state. The effect of disease on performance is also considered briefly. Available data were not considered adequate for study of the relationship between performance and biochemical state and racial origin of the fish.

Size and sex.—Table 14 lists sex composition and length frequency distributions of the various species tested during respective trials in each slope. These data show that sex ratios of fish tested in each of the specific conditions in the 1-on-8 and 1-on-16-slope fishways were not always equal, but differences in the average size of fish passed in the two fishways generally were negligible.

An examination of the effect of size and sex on the performance of fish was made by utilizing appropriate data from tests in the 1-on-16-slope fishway for the period July 24 to September 29 when condition 2 prevailed. Steelhead trout and chinook salmon were the principal species present during this period. As several physical changes were made in the 1-on-8-slope fishway during this same period, data from these trials were not considered in this analysis.

In relating size and sex of fish to their performance, the fork length in centimeters was used to denote size, and performance was expressed in terms of the time (minutes) required to ascend 104 pools. Respective relationships for male and female chinook salmon and steelhead trout are shown in figure 30. With the exception of male steelhead trout, all regression lines exhibit a positive correlation, i.e., the larger the fish the longer

Table 14.—*Length and sex of salmonids tested in endless fishways, 1958*

Species and slope	Condition	Test periods	Number		Fork length—inches				
			Males	Females	Males		Females		Mean, all fish
					Range	Mean	Range	Mean	
Chinook:									
1 on 8	1	June 9 to July 20	7	7	28.0–42.5	31.7	25.6–34.6	31.2	31.4
1 on 16	1		3	9	24.4–26.6	25.5	32.3–40.0	35.6	33.0
1 on 8	2	July 24 to Sept. 7	16	13	19.1–37.0	28.2	25.2–39.6	34.0	30.8
1 on 16	2		23	11	18.3–39.2	29.2	27.8–37.6	32.6	30.4
1 on 8	2A	Sept. 10 and 11	2	3	29.5–30.7	30.1	32.1–37.2	35.0	33.0
1 on 16	2		2	2	30.1–34.3	32.2	33.1–35.6	34.3	33.3
1 on 8	2B	Sept. 12 to 23	9	18	30.3–34.3	32.4	28.1–36.6	31.7	31.9
1 on 16	2		17	17	26.6–41.7	32.2	29.7–38.2	32.7	32.4
1 on 8	[1] 2C	Sept. 24 to 30	6	2	26.0–32.0	28.7	30.0–32.0	31.0	29.3
1 on 16	[1] 2		2	7	24.0–30.0	27.0	28.0–40.0	32.5	31.3
Sockeye:									
1 on 8	1	June 21 to July 20	14	18	16.7–21.7	20.0	15.7–21.5	20.2	20.1
1 on 16	1		18	13	15.4–21.5	18.3	16.7–21.9	20.4	19.1
1 on 8	2	July 23 to Aug. 7	1	3	16.1	16.1	18.7–21.9	20.2	19.1
1 on 16	2		1	1	21.7	21.7	19.9	19.9	20.8
Steelhead:									
1 on 8	2	July 24 to Sept. 2	19	32	21.1–35.4	25.0	20.5–32.9	25.1	25.1
1 on 16	2		13	41	22.4–30.9	24.5	21.1–33.3	25.7	25.4

[1] Lengths estimated. Sex based on external features (not dissected).

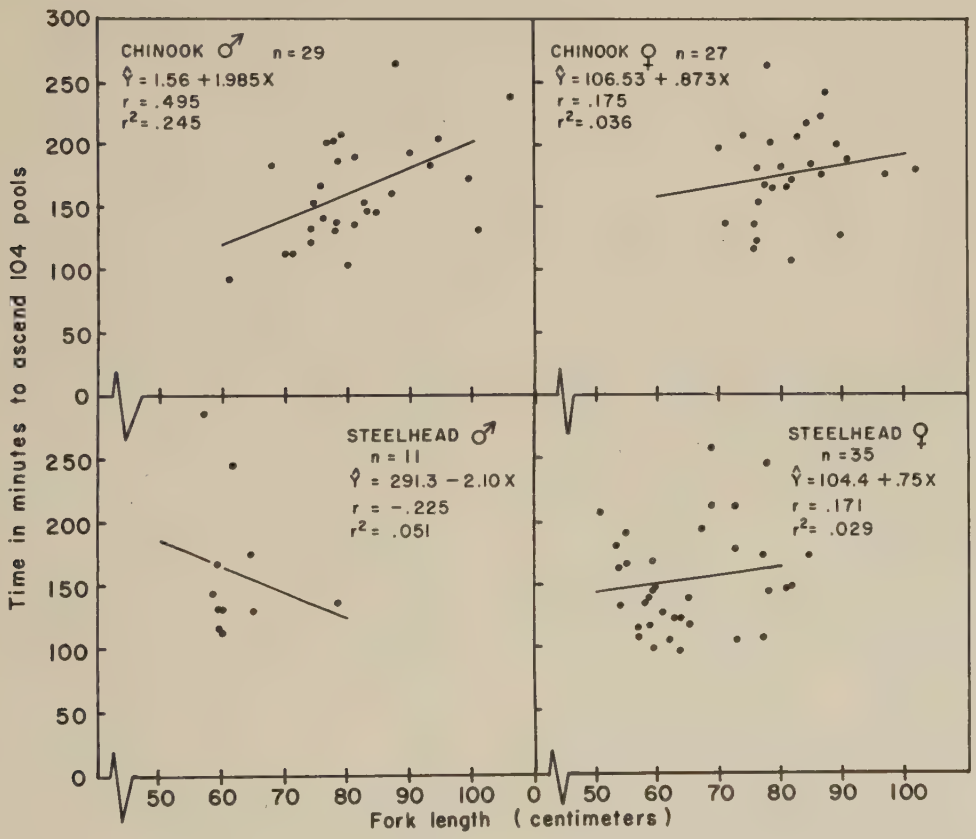

Figure 30.—Relationship between performance and fork length of male and female chinook salmon and steelhead trout ascending 104 pools in a 1-on-16-slope endless fishway. Chinook, September 2 to 29; steelhead, July 26 to August 30.

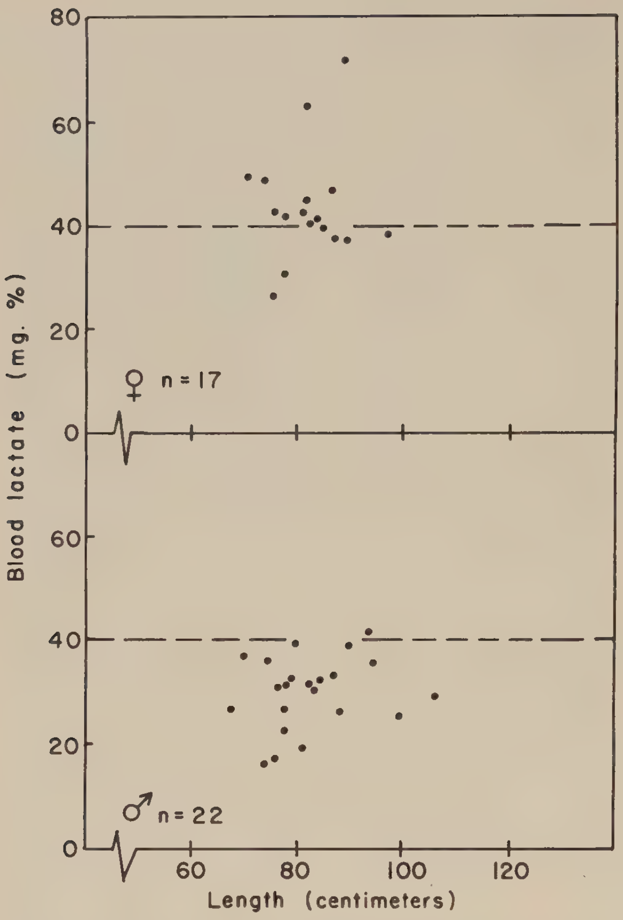

Figure 31.—Levels of blood lactate (mg. percent) in exercised chinook salmon according to length and sex.

the ascent time. Only in the case of male chinook salmon, however, was the regression found to be significant. Therefore, on the basis of these data, size of fish influenced performance only in the case of male chinook salmon.

Testing for the difference in the regression lines between sexes for chinook salmon and steelhead, respectively, no significant differences were found. This suggests performance within species occurred independently of sex.

When respective blood lactate levels were plotted against size of the fish tested in the endless fishways, no relation was found. In chinook salmon, however, the lactate level in females was significantly higher than that in the males (fig. 31). Further opportunity for study of this relation (as yet unexplained) will be afforded when results of a subsequent series of tests conducted in 1959 are analyzed. Lactate levels of male and female chinook salmon ascending the two fishways (1-on-8 and 1-on-16) were re-examined separately. However, no differences between fishways were found.

Sexual maturity.—Comparisons of sexual maturity and performance consider only chinook salmon for the period September 2–23. The state of sexual maturity as used herein was the gonad weight expressed as a percentage of body weight. Performance was again measured in terms of the time required to ascend 104 pools. Steelhead were not utilized in this analysis, because gonad development in virtually every specimen was uniformly immature, generally representing less than 1 percent of the body weight. This may be explained by the fact that spawning in this species usually does not take place until late winter or early spring of the following year. On the other hand, chinook salmon passing Bonneville Dam in September are present in varying stages of sexual maturity. Some may commence spawning within several weeks after passing Bonneville while others bound for the more distant upriver tributaries may not begin spawning for several months.

The relationship between gonad development and the respective performances of male and female chinook salmon is plotted in figure 32. From the figure it is obvious that there was very little agreement between the two variables. The r^2 values indicate that only 1.5 percent of the variation in performance of males and 0.2 percent in the females was associated with variability in gonad development (sexual maturity). The difference between the regressions of males and females was found to be nonsignificant, i.e., there was no difference in performance of males and females with respect to sexual maturity.

Considering the effect of sexual maturity on the biochemical state of the fish tested, blood lactate levels were compared with gonad development and no relationship was found.

Disease.—In the Columbia River a number of highly virulent strains of *Chondrococcus columnaris*, the etiological agent of columnaris disease, have been isolated in adult and young salmon (Rucker, Earp, and Ordal, 1953). These authors further state that strains of this type when tested with young salmon in an experimental hatchery caused mortalities often reaching 100 percent in 12 to 24 hours. Particularly virulent strains appear to be associated with water temperatures in excess

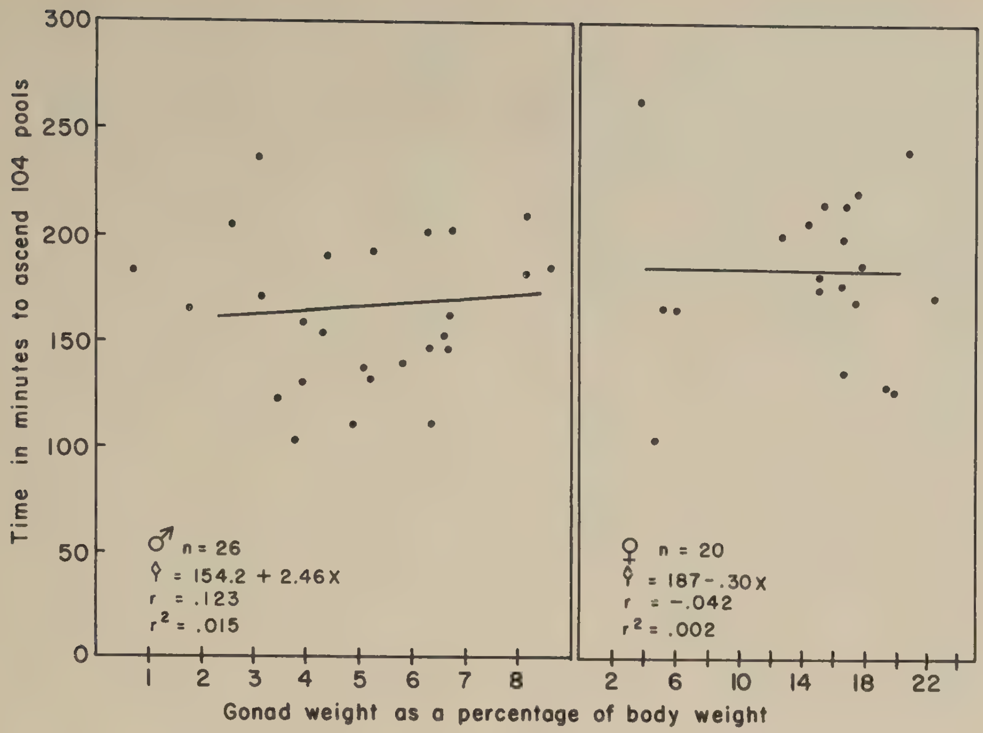

FIGURE 32.—Relationship between performance and sexual maturity. Chinook salmon, September 2–23, 1958.

f 70° F. (Fish and Rucker, 1943; Ordal and Rucker, 1944.)

During our tests from August 6 to September 23, nclusive, 245 salmonids were examined for presnce of *C. columnaris.* Minor to severe lesions vere found in 30 (12.2 percent) individuals. Vater temperatures during this period ranged rom 64° to 73° F.

A comparison of the performance of infected and oninfected fish may be made by examining the assage times of fish tested in the 1-on-16-slope shway, which remained structurally unchanged uring the period when examinations for columaris disease were made. Only steelhead trout nd chinook salmon were sufficiently abundant to e considered in this analysis.

A total of 60 chinook, 7 infected and 53 nonnfected, ascended 104 pools in the 1-on-16-slope shway during these examinations. The seven inected fish had minor to severe lesions from which *. columnaris* was isolated. The mean ascent time r 104 pools among the infected fish was 190 inutes and that of the noninfected group was 170 minutes. This difference in performance was not significant (t=1.06, d.f. 58, P>.2).

Comparison of steelhead performances reveals that 5 infected fish ascended 104 pools in a mean time of 218 minutes while 28 noninfected individuals negotiated the same rise in a mean time of 141 minutes. Passage times for infected fish ranged from 123 to 397 minutes and from 105 to 206 minutes in the noninfected group. Despite the apparent variation in performance of the two groups of steelhead, the difference was not significant (t=1.498, d.f. 4, P>.2). This result possibly may have been influenced by the small sample size of infected fish.

Similar analyses were conducted to determine whether or not the blood lactate level was influenced by columnaris infection. No significant difference between the lactate level of infected and noninfected fish was found for either chinook salmon or steelhead trout. Again, the small sample sizes of infected fish and the degree of individual infection may have been instrumental in affecting the end result of these analyses.

DISCUSSION

One of the most significant aspects of the information gained from the foregoing experiments is the complete lack of evidence for any serious fish fatigue in either test fishway when the proper hydraulic conditions existed. The biochemical measurements on spring chinook and sockeye salmon, admittedly from small numbers of fish with large individual variations, were sensitive enough to detect significant species differences and differences between treatments "terminated" and "volitional," yet were unable to detect a difference between "volitional" fish that had stopped for 1 hour and the unexercised control fish. The implication is that the fish stopped either for reasons other than muscular fatigue or that their fatigue was so slight that they recovered very quickly. The performances of the fish in the fishways appear to bear this out. A review of the performance records of all fish ascending 96 pools or more shows that the fish did not slow down in six complete circuits. As to the sockeye salmon that was permitted to ascend for more than 5 days, there was no indication of fatigue or slowing down for at least 5,000 pools. Most of the evidence seems to point to the conclusion that when suitable hydraulic conditions prevail, the ascent in either of the two fishways is only a moderate exercise for the fish, possibly similar to that of swimming at a cruising speed which can be maintained for long periods of time.

The different patterns of ascent and rates of passage in the 1-on-8-slope fishway illustrate the manner in which hydraulic conditions can influence the pacing of fish movements through a pool-and-overfall fishway. Under condition 1, both chinook and sockeye followed an exaggerated work-and-rest pattern that resulted in the fish spending 70 percent of the time in the turn pools. Under conditions 2A, 2B, and 2C, when the weirs had been restricted to reduce turbulence and introduce lateral eddies in the pools, the fish distributed their time evenly throughout all of the pools. Under condition 2A, the rate of passage in the 1-on-8-slope fishway was much slower than in the 1-on-16-slope fishway even though the pattern of ascent was very similar. Condition 2B produced a rate of passage only slightly slower than that in the 1-on-16 slope (fig. 27), and condition 2C resulted in a rate of passage almost identical (fig. 28) to that in the 1-on-16-slope fishway.

With this clear demonstration of the importance of hydraulic conditions in a fishway, two questions remain to be answered: what is the most desirable rate of ascent, and what are the proper hydraulic conditions to achieve this rate? To either of these questions we have as yet no sure answer. For the purpose of these experiments, we arbitrarily selected as the desired rate the rate of ascent in the 1-on-16-slope fishway now standard on the Columbia River. Further studies will be necessary to determine the range of rates of ascent within which fish will ascend indefinitely without stress or fatigue. How broad this range may be is a matter of great practical interest. There is a strong suggestion in the data (see figs. 21, 27, and 28) that ascending fish may have a tendency to accomplish a definite amount of work per unit time regardless of the pattern of movement or the slope of the fishway. Note how sockeye, with a pronounced run-and-rest pattern of ascent, in the 1-on-8-slope fishway (fig. 21), consistently ascended the 16 pools in the same time as sockeye in the 1-on-16-slope fishway using a very different pattern of ascent.

With a rate of ascent arbitrarily selected, it was possible in these experiments to modify the hydraulic pattern in the 1-on-8-slope fishway by restricting weirs until it produced the desired effect on fish movement. However, the degree to which this solution, satisfactory for an experimental fishway only 3 feet wide and without orifices, will apply to fishways of larger dimensions and different design is a matter of speculation. Clearly, the task of defining "proper hydraulic conditions" is one of the important fishway problems ahead of us.

SUMMARY AND CONCLUSIONS

The effect of fishway slope on fish performance and biochemical state in long fishways was studied with two experimental "endless" fishways constructed so that each made a complete circuit, with the highest pool connected to the lowest pool by means of a lock. Fish that ascended to the top of these fishways were rapidly locked to the bottom pool to begin the ascent again, and in this manner fishways of any desired length were simulated.

The initial experiments were made with turn ools in each fishway that could be used as resting ools. Performances of sockeye showed no signifcant difference between fishways in rates of movenent or in willingness to ascend. For chinooks slower rate of passage in the 1-on-8 fishway was bserved. There was, for both species, a major ifference in patterns of movement in the two shways. A pronounced work-and-rest pattern as observed in the 1-on-8-slope fishway with the sh spending 70 percent of their time in the turn ools while fish in the 1-on-16-slope fishway howed a tendency to distribute their time more venly in all pools. Examination of biochemical ndices of fatigue showed no significant difference etween fishways for blood lactate levels of fish ctively ascending or for fish that had stopped for hour. Significant species differences in blood actate levels and in rates of ascent were noted, ut in neither the biochemistry of the fish nor in heir performance was there any indication of atigue in either fishway. Most of the experinents were with 104-pool ascents, a few with xtended ascents of a few hundred pools, and one ockeye salmon was permitted to ascend more han 6,600 pools before the test was arbitrarily erminated.

A second group of experiments was made with he turn pools in each fishway modified so as to e very turbulent and not suitable as resting areas. Both the chinook and steelhead tested were sigificantly slower in the 1-on-8-slope fishway under hese conditions, and only 43 percent of the hinook salmon in the 1-on-8-slope fishway comleted 100-pool ascents compared to 91 percent n the 1-on-16-slope fishway. Steelhead were qually successful in completing 100 pools in both shways and their well-paced patterns of movenent were similar in each. Chinook salmon apeared unable to pace themselves successfully in he 1-on-8-slope fishway, and the lactate levels of he fish swept back showed definite evidence of istress.

A third set of experiments was done with the urn pools still turbulent but with the weirs of he 1-on-8-slope fishway restricted to reduce pool urbulence and to induce lateral eddies in the pool ow pattern. When the weirs were restricted ith baffles arranged either in line or in alternating sequence, the chinook tested showed a pattern f movement similar to that in the 1-on-16-slope shway. All of the chinook entering the 1-on-8-slope fishway under these conditions completed 100 pools compared to 93 percent completing in the 1-on-16-slope fishway. With in-line baffles the rate of movement was slower in the 1-on-8-slope fishway; with alternating baffles on the weirs the rate of movement in the 1-on-8-slope fishway was equal to the rate in the 1-on-16-slope fishway. There were no significant differences between blood lactate levels of fish ascending either fishway.

Assessments were made of the effect of size, sex, maturity, and disease on performance and biochemical state of the fish. Significant relationships were found only for length of male chinook and performance (larger fish were slower), and sex and lactate level for chinook (female chinook had higher lactate levels). No delayed mortalities resulting from exercise were observed in fish held overnight in each fishway. Initial increases in rates of movement of fish in both fishways indicate that fish learn to ascend. This suggests that changes in hydraulic patterns from pool to pool may adversely influence rates of movement. A tendency for the ascending fish to accomplish a definite amount of work per-unit of time regardless of the slope of the fishway or the pattern of movement was also observed.

The major conclusions reached were:

1. A 1-on-8 slope is as suitable for a long pool-and-overfall fishway for salmonids as the standard 1-on-16 slope provided that the proper hydraulic conditions are obtained.
2. The ascent of a properly designed pool-and-overfall fishway of either slope is only a moderate exercise for salmonids.
3. Hydraulic conditions in the pools can control the rate of ascent and the pattern of movement through a fishway.
4. For all practical purposes, the rate of movement of ascending salmonids will not decrease in the upper end of a long pool-and-overfall fishway and so result in crowding or delay.
5. A 1-on-8-slope fishway with a full weir length overfall and conventional depth (6.5′) in the pools does not have hydraulic conditions desirable for a long fishway and is not recommended for the passage of large chinook salmon.

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APPENDIX

Table A–1.—*Summary of significance tests between salmonid passage times in fishways with slopes of 1-on-8 and 1-on-16*

Species and slope	Condition	n	Mean passage time in minutes 104 pools	d.f.	*t* value	Significance
Chinook:						
1 on 8	1	7	285			
1 on 16	1	8	232	13	1.16	N.S.
1 on 8	2	12	255			
1 on 16	2	28	184	38	3.67	(**)
1 on 8	2A	2	282	------	--------	----------
1 on 16	2	3	193	------	--------	----------
1 on 8	2B	26	209			
1 on 16	2	31	164	38	2.85	(**)
1 on 8	2C	9	151			
1 on 16	2	9	160	16	.49	N.S.
Blueback:						
1 on 8	1	23	168			
1 on 16	1	23	171	44	.36	N.S.
Steelhead:						
1 on 8	2	37	222			
1 on 16	2	46	155	66	5.61	(**)

** Significant at the .01 level.
N.S.—Not significant, $P > .05$.

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